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1 INTRODUCTION

As humans move out from the earth into the Solar system , their most immediate challenge is to provide a life supporting environment in locations that are most devoid of food, air and water. In earlier space flights, life support systems were limited to what may be referred to as open loop configurations. In these configurations, consumables such as water, oxygen and food were stored on board the space craft before the mission. During the mission, these resources were used as necessary and any waste was vented overboard or returned to storage for the duration of the mission. Nothing was recycled.

These open loop ECLSS (Environmental Control Life Support System) configurations worked well for short duration missions. But for long duration missions or to establish a permanent station it is imperative to include regenerative systems in order to reduce the weight of expendables supplied through logistic support.

Autonomy from Earth requires the development of a closed loop ECLSS comprised of human, plant and animal modules. The modules must be integrated with a Waste Management System (WMS) to achieve partial and ultimately long-term self-sufficiency.

Goals and Methods of Approach

Our first goal in this project was to perform a systems analysis of a closed loop ECLSS. This pertains to the development of a model of an existing real system from which to assess the state or performance of the existing system. As far as extraterrestrial life support systems are concerned there are no real systems from

which to derive a model. Therefore, systems analysis is applied to conceptual models obtained from a system design effort. This can serve several purposes:

- (1) To quantify approximate reservoir and flux values of the critical components within the system such as oxygen, hydrogen, nitrogen and carbon dioxide.
- (2) To compare technology candidates for a technology trade study.
- (3) To determine the sensitivity of the system to uncertainty in system variables.
- (4) To serve as a basis for future dynamic modelling of the system.

For our modelling purposes we used a simulator tool called ASPEN (Advanced System For Process Engineering) . The reasons for choosing ASPEN will be elucidated later on in this thesis.

Our second goal was to evaluate the thermodynamic efficiency of the different components comprising an ECLSS. Use is made of the second law of thermodynamics to determine the amount of irreversibility or exergy loss of each component. This will aid design scientists in selecting the components generating the least entropy, as our penultimate goal is to keep the entropy generation of the whole system at a minimum.

2 DISCUSSION OF BACKGROUND MATERIAL

Overview of Life Support System

Under the new space exploration initiative adopted by NASA a permanently manned orbiting platform called Space Station Freedom (SSF) is to be constructed. The most immediate challenge facing scientists is to provide a life supporting environment on the SSF. The open-loop life support systems currently in use by the United States require that the air, food and water needed by humans in space be supplied from the Earth. These same systems are unable to recycle the waste products that result and these must be returned to the Earth or left in space. Since humans require approximately 6.5 kg of potable water, air and food each day, provisions for a crew of four run to nearly 9500 kg per year. In addition, if the crew is to bathe, wash dishes, flush toilets and clean clothes, then the crews needs swells to nearly 28,500 kg of provisions each year, (Rummel,1990). This is the overboard on space operations. As long as mass to orbit is a quantity to be conserved, then recycling of life support commodities represents one of the best ways to lower this overhead.

The objective of a regenerative ECLSS is to recycle the resources required for the mission. This increases the self-sufficiency of the system and creates what is commonly termed as the Closed Loop Environmental Control Life Support System.

The usefulness of the closed loop system is further corroborated by loop closure studies,(Humphries et al., 1986). They considered the on-orbit and resupply weight and volume of a series of impacts ranging from a completely open loop to a closed

loop water and oxygen recovery system. As illustrated in Figure 1, there is a considerable reduction in cost for a closed loop system

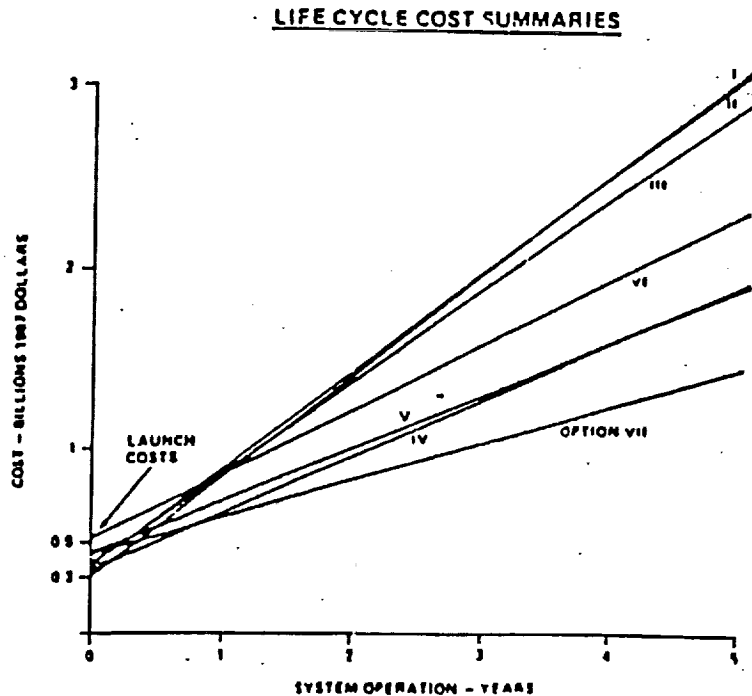


Figure 1: Loop closure cost summaries

where

- OPTION 1 is a completely open system using oxygen resupply, LiOH carbon dioxide removal and water resupply.
- OPTION 2 replaces the LiOH system with regenerable carbon dioxide removal.
- OPTION 3 added an oxygen generation system and processed the condensate water for reuse in the oxygen generator. Excess hydrogen was compressed and returned to the Earth.

- OPTION 4 added hygiene water recovery.
- OPTION 5 added urine reclamation to OPTION 4.
- OPTION 6 added different types of carbon dioxide reduction.
- OPTION 7 combines closed loop oxygen and water recovery systems, adding urine reclamation and potable water recovery to OPTION 6.

Subsystems of the ECLSS

The closed loop life support system can be primarily subdivided into seven subsystems, (Gustavino and Mankamy, 1989). They are :

- (1) THC (Temperature and Humidity Control)
- (2) ACS (Atmosphere Control and Supply)
- (3) AR (Air Revitalization)
- (4) FDS (Fire Detection Subsystem)
- (5) WRM (Water Recovery and Management)
- (6) WM (Waste Management)
- (7) ES (Extra vehicular activity Support)

The functions of the above subsystems are defined in Figure 2.

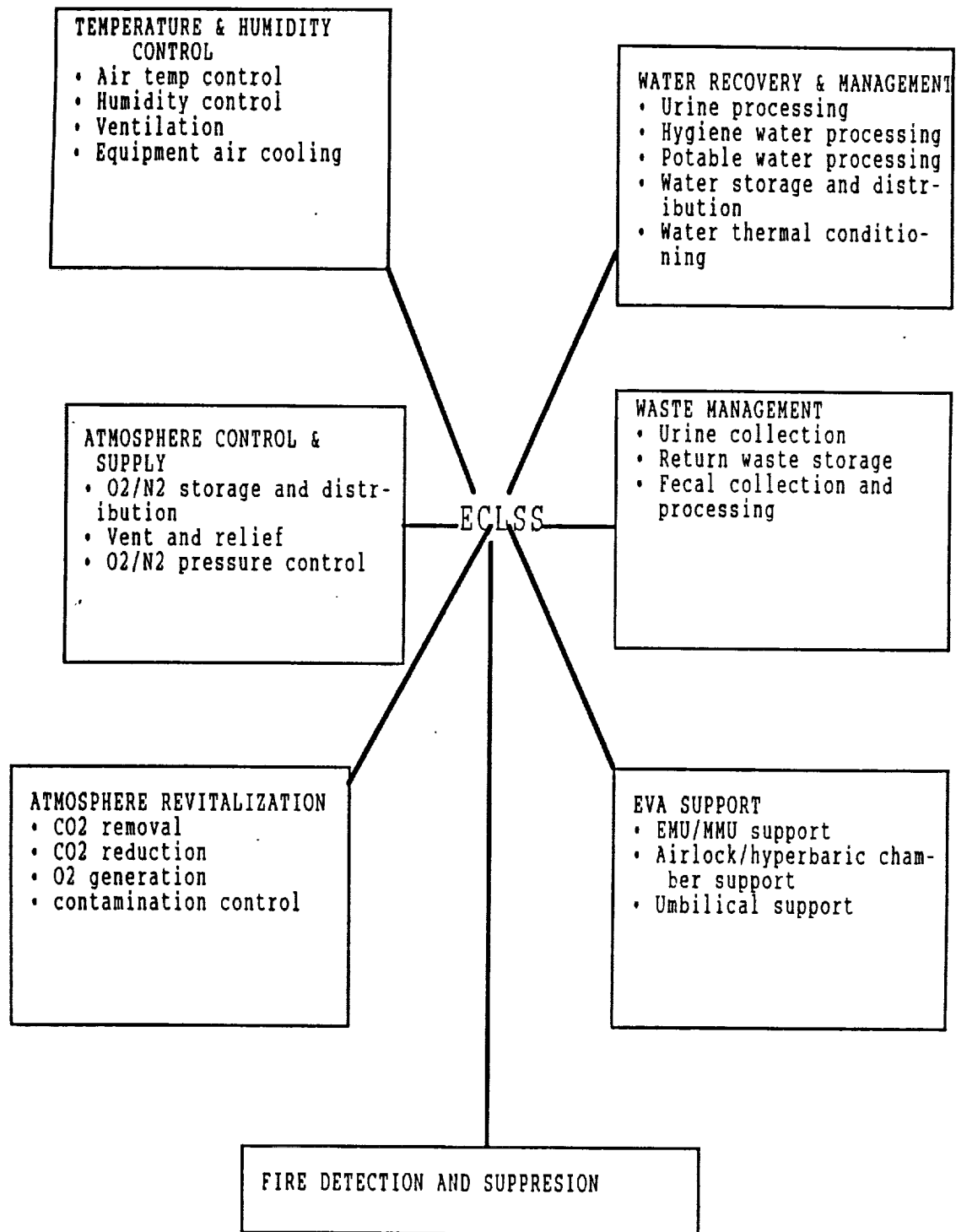


Figure 2: Functional units of the ECLSS (Adapted from Humphries, et al., 1986)

Types of Life Support Systems

There are two types of Life Support Systems :

- Physico-Chemical type
- Bioregenerative type

The **Physico-Chemical** type of Life Support is an example of a medium term regenerative design. In this approach the different subsystems of the ECLSS uses physico-chemical methods to recover metabolic oxygen from respiratory carbon dioxide and fresh water from contaminated water. Food and waste are treated as open loop consumables and expendables. However, the supply of food will also constitute a source of water. The primary source of energy is electrical energy.

The **Bioregenerative** type will provide partial closure of the food loop with food production and partial waste recovery of the plant material (Gustavino and Mankameyer, 1989). The Bioregenerative approach is commonly referred to as the Controlled Ecological Life Support System (CELSS). A CELSS uses plants to imitate the same process that support life on Earth , with one important difference. On Earth there are large buffers to keep the balance between the various elements, but in space these buffers will be minimal. Hence it is very essential to maintain a high degree of control over the process involved. In this system the carbon dioxide which is generated is used by the plants which separate and release oxygen. The carbon is then used along with water and light energy to produce food. After the crop is harvested, the inedible parts of the harvest are used as fertilizers so the portion of the nutrients generated by the plants may be recovered. The primary energy supplier for this design is the sun. Interaction between the different components of CELSS is shown in Figure 3.

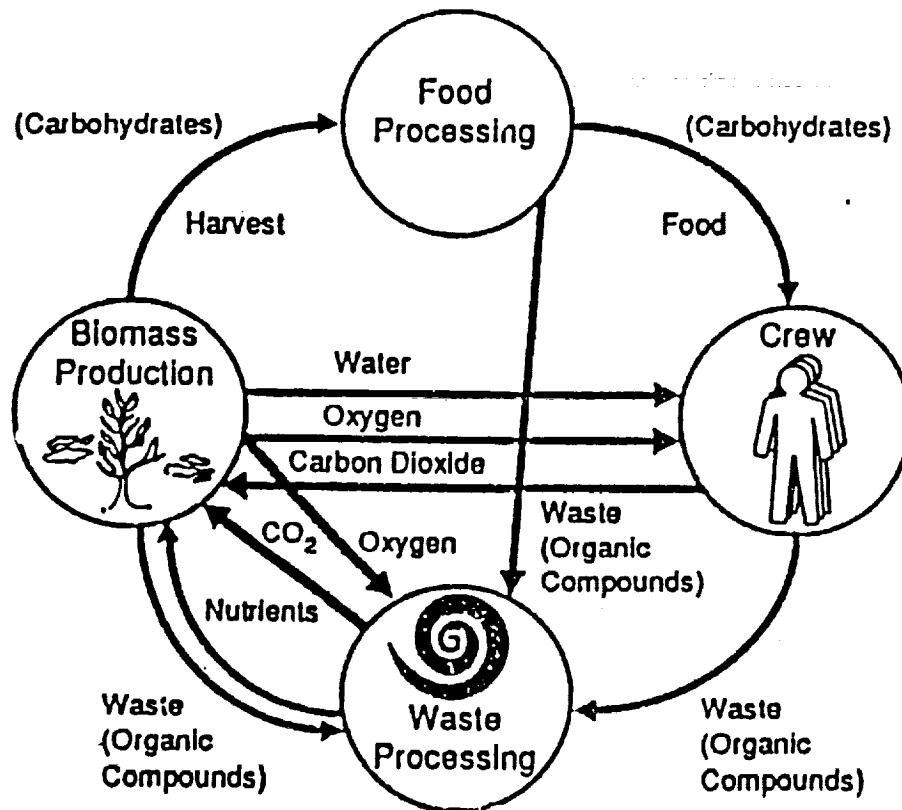


Figure 3 : Various Components of a Bioregenerative Life Support System
(Adapted from Gustavino and Mankameyer, 1989)

Need For Computer Modeling

In order to achieve reliable and economical life support during the various extra-terrestrial missions, critical and difficult choices have to be made:

- At the system level, such as between storing and regenerating essential supplies.
- At the subsystem level, such as between physico-chemical and bioprocessing for regeneration of oxygen;

- At the compartment level such as between the Bosch or Sabatier process for reduction of carbon dioxide.

Computer modeling can be used to evaluate proposed system designs with respect to the above mentioned criteria without carrying out extensive laboratory experiments. Thus, time and money required for technology testing can be reduced.

Computer modeling is also an effective way to check component design specifications and to identify subsystem interface problems. It allows for the examination of critical operating conditions, performance of failure mode analysis and determination of total system performance. This enables the engineer to determine which designs require further development.

Discussion of ECLSS Simulation techniques

In view of the ongoing developments, the applications of an ECLSS simulation tool can be broadly categorised into two divisions, (Simon et al., 1991). These are :

- Mission Analysis
- Assessment of Operational phases.

A major point of interest during mission analysis lies in the budgeting of consumables and disposables such as water and oxygen. For this purpose it is sufficient to determine steady state solutions for most phases of the mission. For the assessment of operational phases such as the launch, transient modeling of the system is used. Transient modeling is also used in failure mode analysis.

In the area of steady state modeling notable work has been done at the Jet Propulsion Laboratory, California, (Seshan et al., 1991) , in developing a Generic Modular Flow Schematic (GMFS) architecture capable of encompassing all functional elements of a physical/chemical life support system. The GMFS is coded in ASPEN. It can be used to compute the material, heat and power flow quantities of every stream in each of the subsystem functional elements for the chosen ECLSS configuration. The input requirements for the GMFS are crew requirements and power data which are obtained from previous bread-board test results. The comprehensive ASPEN material and energy balance output is transferred to a systems and technology assessment spreadsheet for rigorous system analysis and trade studies.

In the field of transient modeling the software to be used by NASA in the 1970's and early 1980's was General Environmental / Thermal and Life Support program (G189A), (Barker et al., 1971). G189A is a complex program written in FORTRAN-5 and FORTRAN-77. It is modularized using numerous subroutines. G189A has a

number of advantages. It offers the advantage of steady-state, quasi-transient or true transient logic. It also has the flexibility of preprocessor and post processor subroutines. However the major limitations of G189A is that it has limited physical property and stream data structures which cannot take into account the different components present in a normal ECLSS. Moreover, advanced technologies can introduce new operations in life support systems which are not modeled by G189A.

In the later half of the 1980's a Computer Aided Systems Engineering and Analysis (CASE/A) ECLSS series was designed as a general ECLSS design and analysis package, (Bangham and Reuter, 1987). This program evolved from both the G189A and SINDA programs and shares the G189A architectural concepts. The designer/analysis interface is graphics based and allows the designer to build a model by constructing a schematic of the system under consideration. CASE/A provides for transient tracking of the flow stream constituents and determination of their state (e.g temperature, pressure, composition) throughout the ECLSS. However the limitations of G189A are also present in CASE/A.

In the European space arena in 1989 a new software was developed called ECOSIM, which is capable of simulating ECLS subsystems, (Perez and Torroglosa, 1991). ECOSIM provides a graphical language. It is based on a set of icons, each representing a specific ECLSS component the user can select to build a complete system schematic. The ECOSIM simulation is based on a mathematical model of the ECLS system under consideration, its environment and the scenario applied. The basic formalism accepted by ECOSIM is a non-linear, state-space continuous time model subject to discrete events. The solution of the mathematical model is then accomplished using a standard implicit differential algebraic equation solver.

Development of an Integrated Steady State model of a Closed Loop Environmental and Life Support System

Our first goal in this work has been to develop a closed loop steady state physico-chemical process model. The distinctive feature of our model which is not present in any earlier work, (Seshan et al., 1991) is that the input requirements for the various ECLSS subsystems is determined from the user written 'crew' model. A Fortran block is appended to the main program to simulate the basic metabolic operations of the crew. The system is completely closed with respect to free water and oxygen, the only inputs being food which includes dry food (i.e carbohydrates, fat and protein) and water present in food. The utility of the crew model and its salient features will be dwelt upon in the following chapter.

Another feature of our approach is a reservoir concept which was adopted throughout the model to improve its versatility. The outlet flows of some subsystems are not directly connected to the inlet of another, but rather are connected to a reservoir. In addition to reducing the modeling effort, this allows for resource sharing among subsystems and would help in sensitivity analysis of the system.

The model is coded in ASPEN (Advanced System for Process Engineering). ASPEN is an application program developed for steady state, chemical process simulation, (ASPEN PLUS USERS GUIDE, 1988). The program allows the user to model a process flow-sheet by sequencing chemical operations similar to an actual process. The program provides basic 'block' operations, such as pumps, mixers, heat exchangers, compressors and other widely used unit operation blocks that a user can put together to represent a chemical process. Over 1000 chemical species, including gases, liquids and solids are available to the user with physical and

chemical property data included. The program also permits the inclusion of user-written FORTRAN subroutines for custom operational blocks. As mentioned earlier, there are other ECLSS simulators available such as G189A and CASE/A. However, in a study by the NASA Ames Research center to evaluate the existing software for life support modelling (Likens and Force, 1988), ASPEN was rated the highest. Hence ASPEN was chosen for our model. The details of ASPEN modelling of the various ECLSS subsystems will be elucidated in chapter 4.

Of the seven ECLSS subsystems mentioned earlier, our model does not take into account the FDS and the ES. The interactions between the other subsystems with the crew is illustrated in Figure 4.

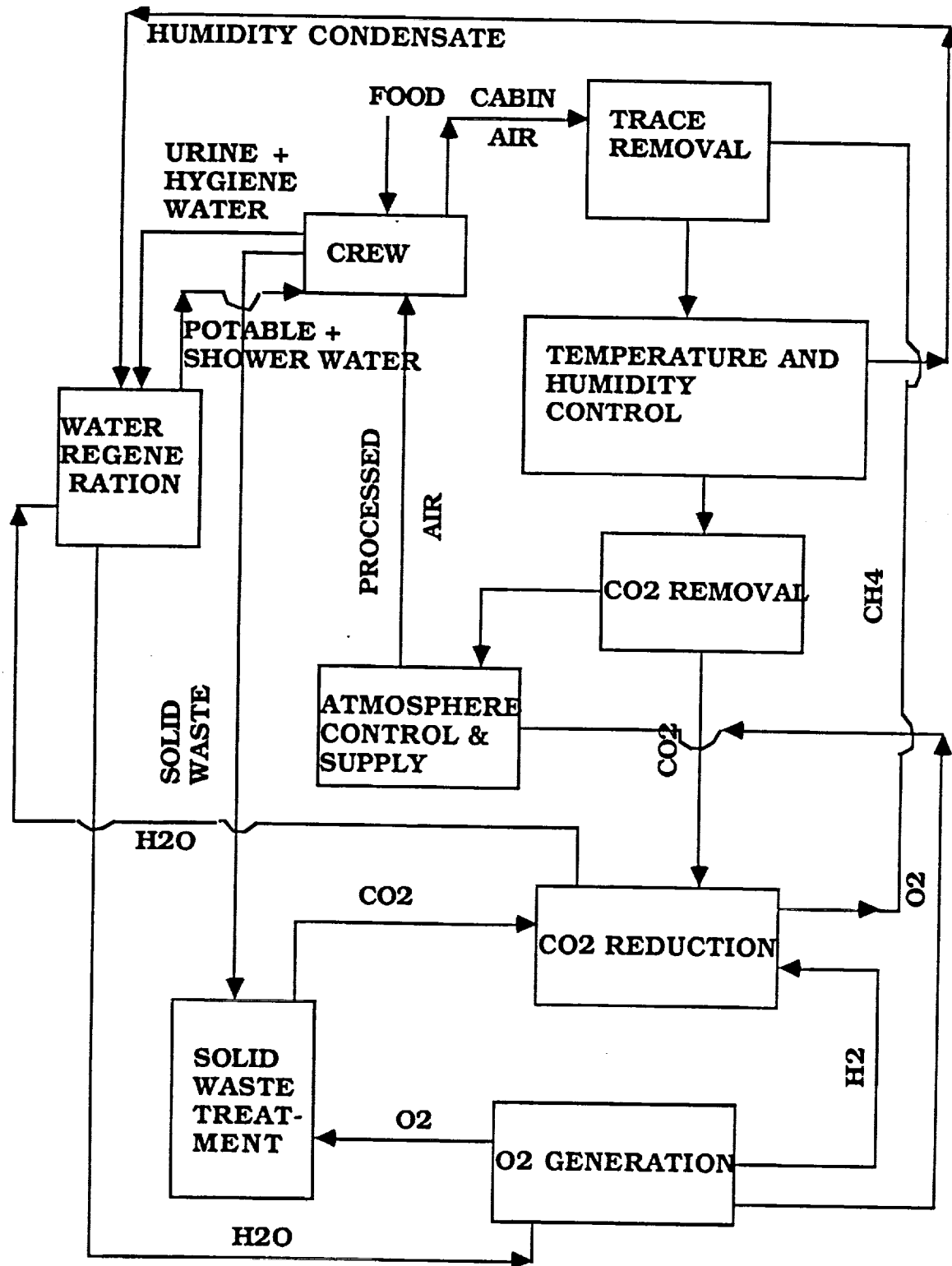


Figure 4: Relationship between the Crew and the Life Support Subsystems

3 HUMAN HABITAT MODULE

The principal components of the human habitat module are

- Crew
- Cabin where the crew is residing

We shall now elucidate the strategies adopted in modeling the crew and the crew living space.

THE CREW MODEL

Need For Development of the Crew model

Long range goals for the space program include the establishment of a man - tended lunar base and human expedition to Mars as a stepping stone towards expansion of humanity into space (National Commission on Space, 1988, and NASA TM, 1988). The requirements of the human module 'drives' the design and operation of an 'ECLSS'. The outputs from the crew model determine the mass flow rates of the different flow streams into the other subsystems of the ECLSS. The objective here has been to develop a computer model to simulate the metabolic inputs and outputs from the crew module, accounting for the human body mass, age and gender and various categories of physical activities. Metabolic inputs to the human module consists of oxygen, food and water while the metabolic outputs include carbon dioxide, solid feces, urine and insensible water (perspiration and respiration).

Model Development

The crew module primarily consists of two subsystems : inputs and outputs. In developing this model the following assumptions were made:

- With the functional dependence of energy activity upon gravity not being clearly understood due to lack of available experimental data it was assumed that the basic relationships which are obtained for terrestrial data hold under reduced gravity conditions. It is however expected that energy expenditure rate in fractional gravity (e.g Lunar $1/6$ g or Martian $1/3$ g) is smaller than at 1g for a given activity (Sadeh, 1989).
- The crew is at steady state so there is no accumulation of food or water by any individual, i.e the weight of the individual remains the same.

The premise of this study is then that all of the input/output streams to the crew module are determined by the energy expenditure rate .

The crew module is now determined based on the following considerations:

- Determination of basal metabolic rate.
- Energy activity
- Metabolic input requirements
- Metabolic wastes.

Basal Metabolic Rate

Basal metabolic rate or basal energy expenditure is defined as the heat expended by an individual at least 10 hours after the last meal, resting in a lying position, awake, at a normal body and ambient temperature and without any physical or physiological stress. The basal metabolic rate is expressed in Kcal per day per square meter of body surface.

The basal metabolic rate is a function of age, body mass and gender. It is evident that there is a non - negligible influence of age on energy expenditure, (Fleisch 1951). Also, it is known that the magnitude of energy expenditure is a function of the amount of active cells in the body or body cell mass. Women have more adipose tissue and less muscle than men, and therefore have a lower metabolic rate than men.

Hence the following equations as suggested by Dreyer in 1920 , can be used to compute the basal metabolic energy of men and women from the age of 5 onwards, (Sherman, 1952)

$$\text{Male : BEE} = \frac{W^{0.5}}{0.1015 \times A^{0.1333}} \quad (1)$$

$$\text{Female : BEE} = \frac{W^{0.5}}{0.1127 \times A^{0.1333}} \quad (2)$$

where BEE : Basal metabolic rate /Basal energy expenditure in Kcal
per 24 hours

W : weight in grams

A : age in years

Energy Activity

The crew members of Space Station Freedom will be engaged in a wide variety of on base " shirt-sleeve " earthlike activities. It is assumed that the crew will be engaged in four basic human physical activities :

- (1) Rest/Lying
- (2) Walking
- (3) Sitting

(4) Running

According to our assumption that terrestrial relationships hold good in the space station, we can use the following relationships to express the different human activities in terms of the basal metabolic rate, (Lusk,1928).

ACTIVITY	ENERGY EXPENDITURE
Lying	BEE
Walking	2.57BEE
Sitting	1.23BEE
Running	7.86BEE

where BEE : basal energy expenditure in Kcal/hr

Figure 5 depicts the influence of the energy activity on the crew.

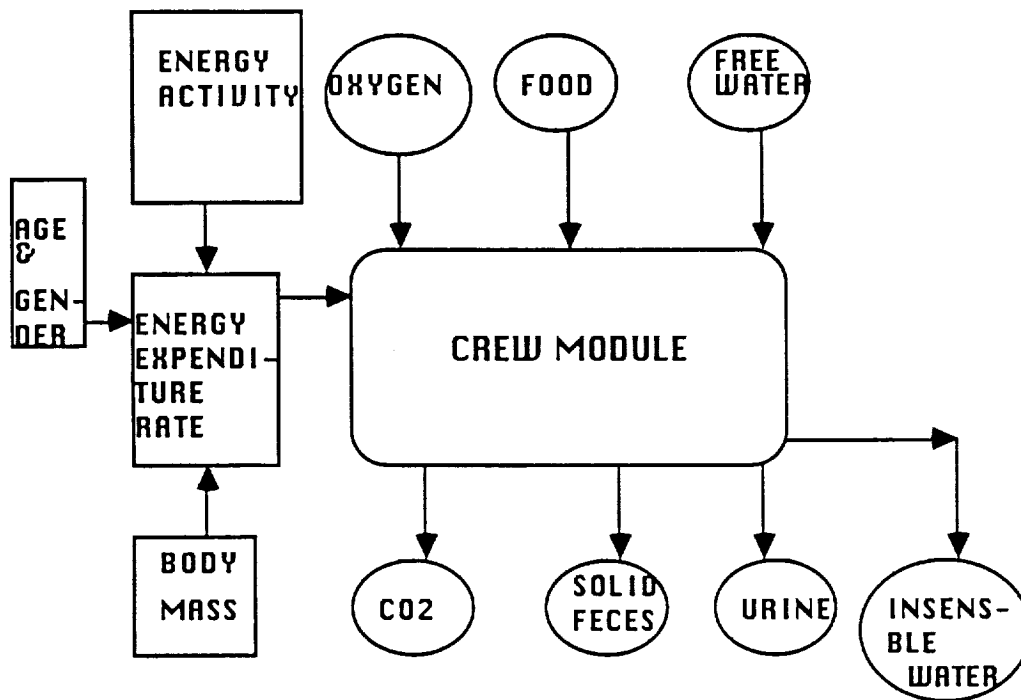


Figure 5: Metabolic mass flow rates for the human module (Adapted from Sadeh et al., 1989)

Metabolic Input Requirements

Metabolic inputs for the human module consists of food (dry food together with water in food), oxygen and water as shown in Figure 5 above. The mass flow rates of these metabolic inputs was expressed in terms of the energy expenditure by the crew in one hour.

Dry Food Consumption

Dry food is the main source of energy to the body and consists of macro and micro nutrients and vitamins. The major components of dry food are the macro nutrients which are composed of carbohydrates, proteins and fats. Consequently, for our modelling study here we only have to take the major macro nutrients into consideration.

The normal diet of a person consists is taken as 200g of carbohydrates, 70g of protein and 60g of fat, (Lehninger, 1977). Using the same composition as prescribed by Lehninger for the crew, we can express the mass fraction of protein and fat in the diet in terms of carbohydrate present as

$$P = 0.35 \times C \quad (3)$$

$$F = 0.30 \times C \quad (4)$$

where

P = amount of protein in diet in grams

F = amount of fat in diet in grams

C = amount of carbohydrate in diet in grams

For our calculation the representative compounds used as typical carbohydrate, fat and protein were Glucose ($C_6H_{12}O_6$), Palmitic Acid ($CH_3 [CH_2]_{14} COOH$) and Alanine ($NH_2CH [CH] COOH$) respectively, (Stokes, 1988).

All the energy required by man is obtained from food. The energy produced through metabolism of one gram of carbohydrate, fat or protein is 4.17, 9.3 or 4.3 Kcal respectively (Bursztein et al., 1989)

Knowing the energy expenditure of a crew member (man/woman) in one hour, the amount of food required is thus computed as

$$TEE = 4.17 \times C + 9.3 \times F + 4.3 \times P \quad (5)$$

where

TEE - Total energy expenditure

From (3) and (4) the amount of fat and protein can be expressed in terms of equivalent carbohydrates. Thereby, the total carbohydrate required for metabolism is

$$C = \frac{TEE}{(4.17 + 9.3 \times 0.3 + 4.3 \times 0.35)} \quad (6)$$

However, it is known that when food is eaten, not all of it is absorbed, some passes through the intestine and is excreted in feces. From literature it is known that approximately only 93 % of protein and 98 % of fat are metabolized, (Merrill and Watt, 1955, Southgate and Durnin, 1970). On this basis the actual amount of carbohydrate, fat and protein to be supplied in diet can be computed. Thus the total dry food requirement (TDF) is given by

$$\text{TDF} = \frac{C}{0.98} + \frac{F}{0.98} + \frac{P}{0.93} \quad (7)$$

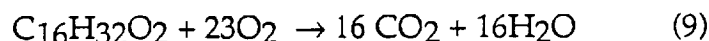
Oxygen Requirement

Oxygen is required for the metabolism of carbohydrates, fat and protein. Stoichiometric relations for the metabolism of the three macro - nutrients is given below :

Carbohydrate



Fat



Protein



From the above relations (8), (9) and (10) we can deduce that for metabolizing 1gram each of carbohydrate, fat and protein we require 0.85, 2.29 and 0.86 liters of oxygen respectively at body temperature and pressure. Thereby

$$\text{VO}_2 = 0.85 \times C + 0.86 \times P + 2.29 \times F \quad (11)$$

where

VO_2 is the amount of O_2 consumed in liter per hour

Water Requirement

The total water input to the crew consists of metabolic water H_2O_M (i.e water produced through the metabolism of food), water in food and free/drinking water. Apart from this the crew also requires water for their daily activities like shower, laundry etc. This is termed as hygiene water.

Metabolic water is produced through the physical and chemical processes involved in the metabolism of dry food. The metabolic water mass flow rate is proportional to the consumption of macronutrients as shown by the stoichiometric relation below. This was derived on the basis of reactions (8), (9) and (10).

$$H_2O_M = 0.6 \times C + 0.51 \times F + 1.125 \times F \quad (12)$$

The amount of water associated with dry food is 1.32 lb per lb of dry food, (Hall, 1990). Knowing the amount of dry food consumed we can thus evaluate the amount of water entering through food.

Water required for drinking is calculated by performing a water balance over man. Since the man is assumed to be at steady state there is no overall accumulation of water in man. As shown in Figure 5, the output water streams from the crew are urine and insensible water. The mass flow rates of these output water streams is determined as a function of energy expenditure. Hence, water required for drinking is the difference between the total water output and the summation of water input in the form of metabolic water and food water.

Metabolic Wastes

In a closed loop ECLSS the metabolic wastes from the crew are treated, recycled and managed for utilitarian use. Metabolic waste outputs from the crew consists of carbon dioxide, solid feces, urine and insensible water (this includes perspiration and respiration water) as shown in Figure 5. In addition the crew also generates a wide variety of non metabolic wastes such as hygiene water, food packaging wastes and manufacturing wastes. In our model only hygiene water is taken into consideration in this category.

Carbon dioxide

As shown in reactions (8), (9) and (10) carbon dioxide is produced during the metabolism of macro nutrients. Thereby, from the above mentioned relations it is computed that on metabolism 1g of carbohydrate, fat and protein each produces 0.85, 1.59 and 0.71 liters of carbon dioxide respectively at body temperature and pressure.

$$VCO_2 = 0.85 \times C + 0.71 \times P + 1.59 \times F \quad (13)$$

where VCO_2 is the amount of CO_2 produced in liters in hours.

Feces Production

Here we are only taking into account the solid feces production. An input /output mass balance implies, to a first approximation, that the feces production is equal to the dry food inputs less the amount of food metabolized by the body. Going by the above analogy the total amount of solid feces is

$$SOLID\ FECES = TOTAL\ FOOD - METABOLIZED\ FOOD$$

$$\text{SOLID FECES} = \left(\frac{\text{INTAKE}}{\frac{C}{0.98} + \frac{F}{0.98} + \frac{P}{0.93}} \right) - (C+F+P) \quad (14)$$

Urine Production

Urine is composed of liquid and solid particulates and daily average values of the various constituents of urine as obtained from (NASA database,1992) is shown in Table 1.

Table 1 : Composition of Urine Analog (Adapted from NASA database)

Substance	Amount (person/day)	Su
Water	1454 ml	Wa
Urea	21.0045 g	
Chloride	8.836 g	
Sodium	4.9376 g	
Potassium	3.80746 g	
Sulfate ion	3.251 g	
Creatinine	2.3572 g	
Hippuric acid	1.77958	
Citric acid	0.995362 g	
Glucuronic acid	0.949905 g	
Ammonia	0.849585 g	
Uric acid	0.73359 g	
Tyrosine	0.681862 g	

The principal constituent of urine is urea, which is formed during protein metabolism as shown in (10). Thus the amount of urea present in urine is

$$WRU = 0.332 \times P \quad (15)$$

where WRU is the urea produced in grams

We make an assumption here that the urine urea concentration of the crew remains constant irrespective of the crew exercise level. From Table1, the amount of water to be associated with the urea to obtain the desired urine concentration is

$$WU = WRU \times \frac{1454}{21.0045} \quad (16)$$

where WU is amount of water in urine in ml.

Insensible Water Production

Insensible water is produced by perspiration and respiration from the crew members.

When the crew members are at a resting neutral steady state the body core temperature of an individual remains constant at 98.6 °F. When the crew is engaged in activities which expend energy in excess of basal metabolic activity, the sweat production increases in order to keep the body core temperature at the desired value by removing more heat from the body surface by evaporation of sweat. This is illustrated in Figure 6, which shows sweat production in gm per hour as a function of energy metabolism, (Stegemann, 1977). It is observed that there is a disproportional rise in sweat production in relation to the increase in energy metabolism

From Figure 6 linear relationships between energy metabolism and sweat production were derived. When energy metabolism is less than or equal to 250 Kcal/hour ,

$$SW = 1.50 \times (\text{energy metabolism}) - 75 \quad (17)$$

For energy metabolism greater than 250 Kcal/hour

$$SW = 2.50 \times (\text{energy metabolism}) - 325 \quad (18)$$

where SW is the amount of sweat produced in grams

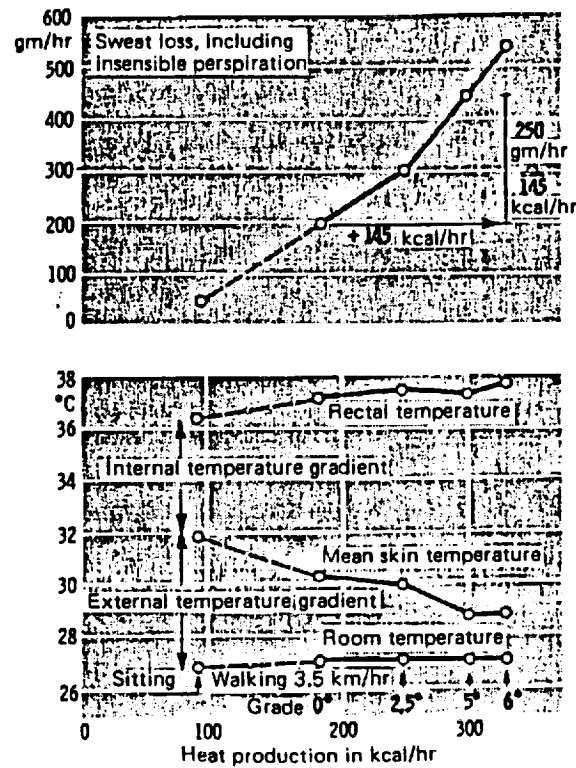


Figure 6 : Sweat loss in man at different levels of heat production.(Adapted from Stegeman, 1977)

Water lost by respiration is equivalent to the amount lost in saturating the inspired air. The partial pressure of water vapor in inspired and expired air is 15 and 47 mm Hg respectively, (Seagrave, 1971). Thereby total volume lost as respiration is the difference in volume of water in expired and inspired air. Procedure to calculate the total volume of inspired and expired air will be dealt with in the next section.

CABIN MODEL

The cabin model is used to maintain the requisite environmental criterion in the cabin at 20.8% oxygen, 76.9% nitrogen, 0.3% carbon dioxide and 73.7% relative humidity at 70 ° F (Humphries et al., 1986). In order to maintain the cabin at this desired level of habitability we need to regulate the amount of air flowing into the cabin.

Within the cabin there is continuous gas exchange between the cabin air and the crew. The crew is continuously breathing in oxygen rich air and breathing out carbon dioxide rich air.

Hence prior to determining the air flow rate into the cabin it is imperative to calculate the mass flow rates and composition of the inspired and expired air. We propose to evaluate the mass flow rates and composition of the inspired and expired air based on the compartmental model of the human respiratory tract. The respiratory system of a human being includes the nose, nasal cavity and sinuses, the pharynx, the larynx, the trachea and smaller conducting passageways leading to the exchange surfaces of the lungs, (Martini, 1989). The inspired air which enters through the nose is filtered, humidified and warmed in the respiratory tract before reaching the alveoli in the lungs where gaseous exchange takes place. We shall now outline the procedure for modeling this entire respiratory mechanism.

We start with the compartment model of the human lung, (proposed by Seagrave 1971) to develop a more detailed model of the respiratory tract. It takes into account the volume and heat changes undergone by the inspired air by dividing the respiratory tract into three compartments. These are

(1) Upper respiratory tract where the inspired air is heated to the body temperature of 98.6 °F.

(2) Lower respiratory tract where the inspired air is saturated with water vapor. The partial pressure of water vapor at body temperature is 47mm Hg.

(3) Lungs, where O₂ which is required for metabolism is lost from the air to the blood in the pulmonary circuit and CO₂ which is produced during metabolism is added back to the air from the blood. Figure 7 depicts the model with all the input and output streams.

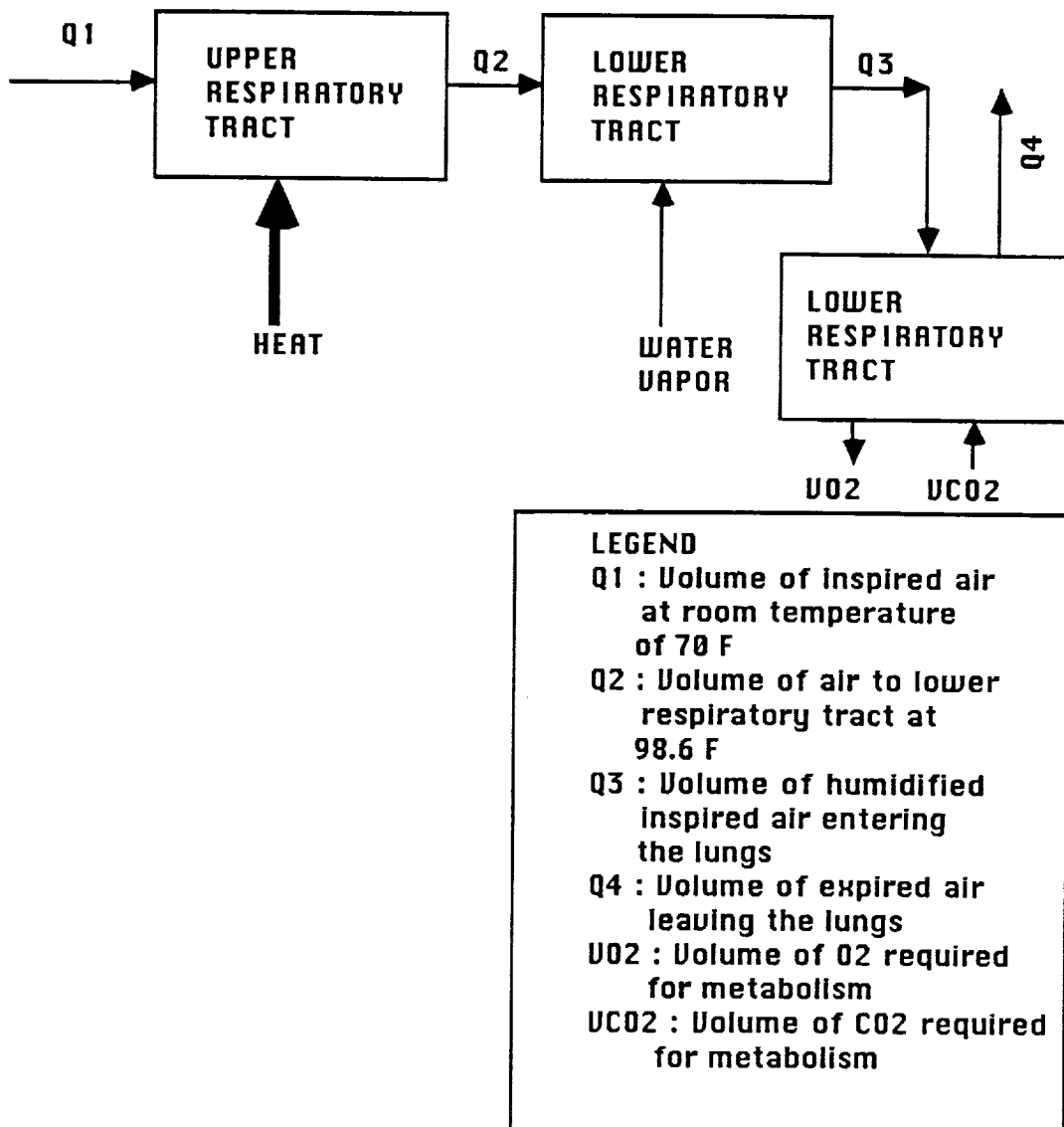


Figure 7: Compartmental model of the Respiratory tract.

The basic assumptions in our model are :

(1) All the compartments are considered to be homogenous and well mixed so that concentration of each species at any time is uniform throughout each compartment.

(2) The total pressure of air at any position within the respiratory tract is 760 mm Hg.

(3) Ideal gas law holds in each compartment.

(4) The total volume of oxygen required for metabolism does not rise above 3 lit/min at any instant, i.e the maximum permissible exercise limit of the crew is about 12 times the basal metabolic rate.

In our model we will follow only four significant molecular species in the gas and assume that any other species are present in negligible amounts. The four species to be followed are nitrogen, oxygen, carbon dioxide and water. The fundamental principle which is used to compute the mass flow of each species is

$$\begin{array}{lcl} \text{rate of} & = & \text{input flow rate} + \text{generation} - \text{degradation or} \\ \text{accumulation} & & \text{or production} \quad \text{consumption} \end{array}$$

Since this is a steady state model the rate of accumulation is equal to zero. The detail of equations used for each compartment is given in Appendix 1.

Upper Respiratory Tract

No material exchange is taking place. The inspired air is heated to body temperature. The relation between the volume of air entering and leaving the compartment is given as

$$Q_1 = 1.054 \times Q_2 \quad (19)$$

where Q_1 is the volume of air entering in liters per hour
 Q_2 is the volume of air leaving in liters per hour.

Lower Respiratory Tract

The heated inspired air is saturated with water vapor. The volume of air leaving the compartment can be expressed as

$$Q_3 = 1.045 \times Q_2 \quad (20)$$

where Q_3 is the volume of air leaving the compartment in liters per hour.

Knowing that the air leaving the compartment has a partial pressure of water of 47 mm Hg and that there is no exchange of other species namely oxygen, carbon dioxide and nitrogen, the mole fractions of the components in the gas exiting the lower respiratory tract is calculated as

$$\text{Mole fraction of oxygen (} Y_{O_2^i} \text{)} = 0.199$$

$$\text{Mole fraction of nitrogen (} Y_{N_2^i} \text{)} = 0.735$$

$$\text{Mole fraction of carbon dioxide (} Y_{CO_2^i} \text{)} = 0.004$$

$$\text{Mole fraction of water (} Y_{H_2O^i} \text{)} = 0.062$$

Lungs

The following material balance equations can be written for the lungs.

Volume of O_2 inspired = Volume of O_2 expired + Volume of O_2 lost to blood

$$0.199 Q_3 = Q_4 \times Y_{O_2} + V_{O_2} \quad (21)$$

Volume of CO_2 inspired = Volume of CO_2 expired - Volume of CO_2 gained from blood

$$0.004 Q_3 = Q_4 \times Y_{CO_2} - V_{CO_2} \quad (22)$$

Volume of N_2 inspired = Volume of N_2 expired

$$0.753 Q_3 = Q_4 \times Y_{N_2} \quad (23)$$

Mole fraction of gases in expired air = 1.0

$$Y_{CO_2} + Y_{N_2} + Y_{O_2} = 0.938 \quad (24)$$

where

Y_{CO_2} is mole fraction of CO_2 in expired air

Y_{N_2} is mole fraction of N_2 in expired air

Y_{O_2} is mole fraction of O_2 in expired air

Q_4 is volume of expired air in liters per hour

From Figure 8, (Passmore and Robson, 1969) it is found that pulmonary ventilation (V_E) increases in proportional to volume of O_2 uptake at STP upto a certain point which is equal to 3 liters per minute of VO_2 beyond which V_E increases more than the corresponding O_2 uptake.

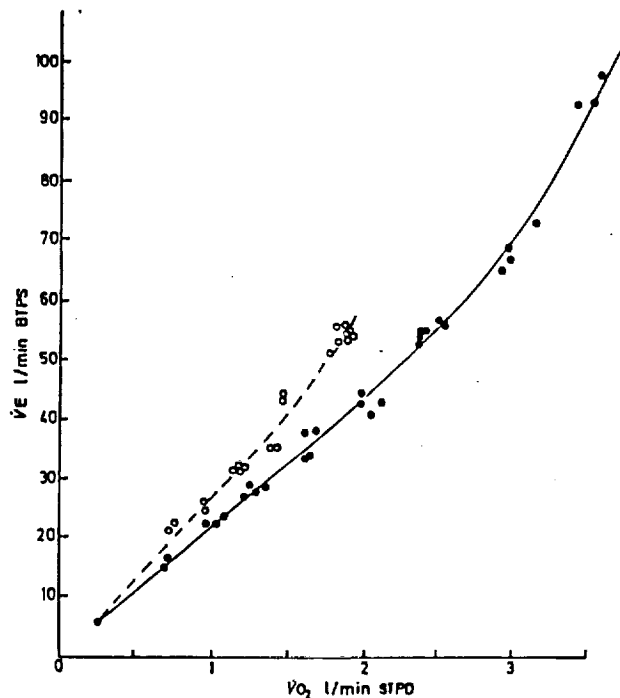


Figure 8: V_E in relation to VO_2 (Adapted from Passmore and Robson, 1969)

In accordance with our third assumption it is justified to assume a linear relationship for O_2 uptake and V_E . This is given by

$$V_E = 24.55 \times MO_2 + 0.1125 \quad (25)$$

where

V_E is volume of gas entering the lungs in liters per minute at body temperature and saturated conditions

MO_2 is volume of O_2 required for metabolism in liters per minute at STP and dry conditions

Knowing the volume of inspired and expired air and their respective mole fractions, we employ the ideal gas relation ($PV = mRT/M$) to calculate the total mass flow rate of each gaseous component in expired and inspired air.

ASPEN model of the cabin

For modeling purpose the cabin is modelled as two compartments in series. The inputs and outputs of each compartments is shown in Figure 9.

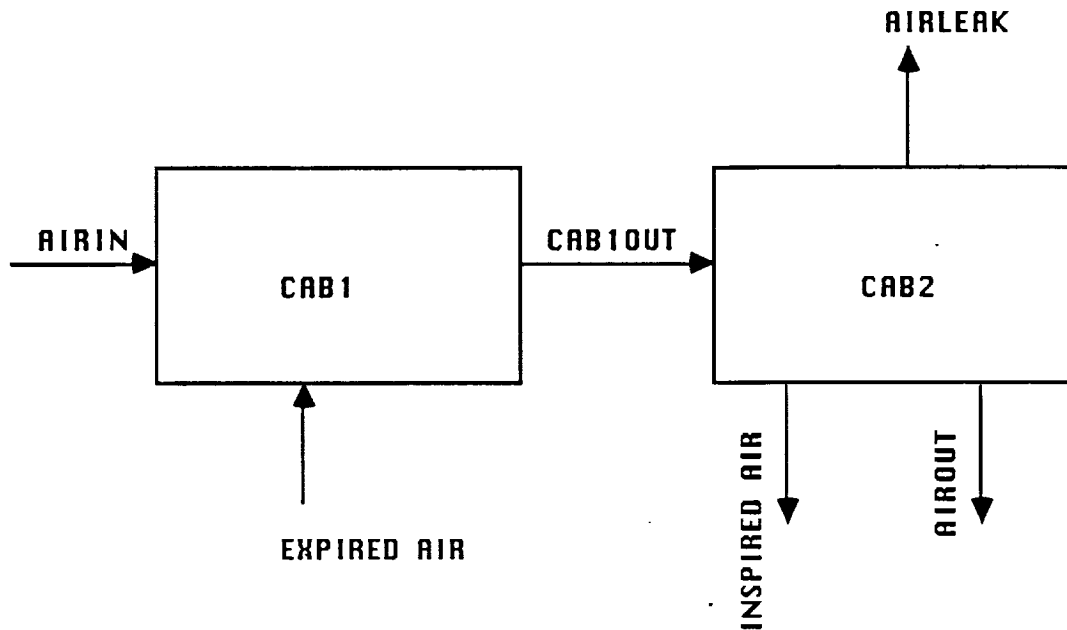


Figure 9: Model of Crew Habitat

There is a constant leakage of 6.5×10^{-4} lb/hour of gas from the cabin, (LiSSA,1992).

For the purpose of maintaining a comfortable living condition within the cabin we need to regulate not only the composition of air within the cabin but also the temperature and air motion. The design flow rate of air into the cabin is calculated from the following relation, (Haines,1988)

$$CFM = \frac{q_s}{TD \times AF} \quad (26)$$

where

CFM is design flow rate in cubic feet per minute

q_s is sensible cooling load in btuh

TD is design temperature difference between cabin and supply air

AF is the air factor

The Air Factor is used to take into account the variation in air density. The Air Factor is given by, (Haines, 1988) :

$$AF = \text{Density} \times SH \times 60 \quad (27)$$

where Density is air density at design temperature and pressure
 SH is specific heat of air, btu per lb, at design temperature
 and pressure

For standard conditions, AF is equal to 1.08 btuh/cubic feet per min °F

As considerable energy will be expended in cooling the supply air to a low temperature we assume that the supply air is nearly at the room temperature of 69°F..

The cooling load is equal to the amount of heat lost by the crew. Since the crew is at a steady temperature the total heat lost by the crew is equal to their metabolic activity.

The ratio of CFM and inspired air is then used as a basis to preset the ratio between INSPIRED AIR and AIROUT.

In the ASPEN model the first compartment (CAB1) was modelled as a MIXER and the next compartment (CAB2) was modelled as FSPLIT with the volume ratio between INSPIRED AIR and AIROUT being predetermined. A feedback control mechanism was used to regulate the amount of air flowing into the cabin. The mass flow rates of the different gaseous components in the inspired air were the set variables, while the corresponding mass flowrates of the air into the cabin i.e AIRIN were the manipulated variables. This was accomplished in our ASPEN model using Design Specifications.

4 MODELING ECLSS SUBSYSTEMS

This chapter discusses different functional units comprising each subsystem of the closed loop ECLSS. Though each subsystem can have a wide variety of technologies, for our modeling purpose either one or two sample technologies were chosen for each subsystem. The modeling technique adopted was either to simulate each major piece of equipment or to simulate the functional performance of the functional unit.

For our modeling purpose we used ASPEN. The reasons for choosing ASPEN over other chemical process simulators, were elucidated in chapter 2.

However certain difficulties were encountered in modeling with ASPEN. ASPEN is not equipped to provide detailed models of electrolyte process, so the electrolysis model, as in water electrolysis process, lacks fidelity in kinetic characterization of electrode reactions. No provision is made in ASPEN for the participation of electrons in the electrode reactions so the cell reactions are modelled as chemical rather than electrochemical process.

Another difficulty is encountered in modeling membrane technologies. ASPEN has no routines for modeling membrane based separations. The membrane based CO₂ removal system was therefore modeled using a user written FORTRAN block.

Lastly, ASPEN is a steady state modeling tool and so difficulties are to be encountered in modeling dynamic process.

Water Reclamation Subsystem

Water reclamation involves process to reclaim water from sources such as carbon dioxide reduction, cabin humidity condensates, wash water (from clothes, dishes

and hygiene) and urine. Usually the average flow rates of wash water and urinal flush water are taken as 12 lb/day and 1.09 lb/day respectively, (NASA database,1992).

The flow rate of urine is determined from the metabolic rate of the crew (shown in chapter 3). The procedure to calculate the amount of humidity condensate will be outlined in the section on Atmosphere Humidity Control.

The basic functions of the water reclamation system can be listed as, (Huttenbach and Radford, 1965) :

- Collection of waste water.
- Pre-treatment of waste water to inhibit the growth of bacteria and improve the performance of phase change process.
- Reclamation of water using a multifiltration, membrane or phase change process. In general membrane and multifiltration processes are used to treat less contaminated streams such as humidity condensate and CO₂ reduction process as while phase change processes are used to recover water from urine and hygiene water.
- Post treatment of recovered water to remove residual contaminants.
- Storage, distribution and thermal conditioning of recovered water.
- Monitoring the quality of recovered water.

Multifiltration

A multifiltration process includes a particulate/bacterial filter, an activated charcoal canister, an anion exchange resin bed and a cation exchange resin bed, (Popoma and Collins, 1965).

Membrane Process

Membrane Process include Reverse Osmosis and Electrodialysis. Generally spiral wound, tubular and tube side hollow fiber membranes are used. The membrane processes have the advantage of less power consumption and heat rejection over conventional phase change process. However, they have the disadvantage that the water to be treated by these processes require a greater degree of pretreatment as compared to conventional phase change process. Moreover, most conventional membranes are unable to withstand high temperatures sufficient for sterilization (Schubert, 1983).

Phase Change Process

Phase change processes involve distillation and condensation, with a goal to retain the solutes (in sterilized form) in the evaporator and to reclaim the energy required for the vaporization process. The phase change processes that are commonly used are air evaporation, vapor compression distillation, thermo electric integrated membrane evaporation subsystem, and vapor phase catalytic ammonia removal.

Since phase change processes are used for the treatment of bulk waste water such as urine and hygiene water, we have only considered the phase change process for our water regeneration process. Two sample technologies which were studied are Vapor Compression Distillation (VCD) and Thermo electric Integrated Membrane Evaporation Subsystem (TIMES).

Vapor Compression Distillation

Process Description :

A schematic of a VCD is shown in Figure 10. The recovery of latent heat in the VCD is accomplished by compressing the vapor to raise its saturation temperature and

then condensing the vapor on a surface which is in direct contact with the evaporator. The resultant heat flux from the condenser to the evaporator is sufficient to evaporate an equal mass of water. Thus the latent heat of condensation is recovered by the evaporation process and the only energy required for the process is that necessary to compress the vapor and to overcome the thermal and mechanical inefficiencies. The VCD process occurs in a 70°F to 95°F temperature range by maintaining a nominal condenser pressure of 0.7 psia, (Quattrone, 1981).

As shown in Figure 10, there are two tanks, the recycle tank and the waste water tank which are maintained at a pressure of 20 psia. The still is evacuated to a saturation pressure of 0.5 psia operating at a temperature of 70 °F. Pretreated urine and waste water are stored in the waste water tank and is then sent to the recycle tank. The process is continued till the solids concentration in the recycle loop increases to greater than 50%. The process is then stopped, the brine is removed and the VCD is then restarted.

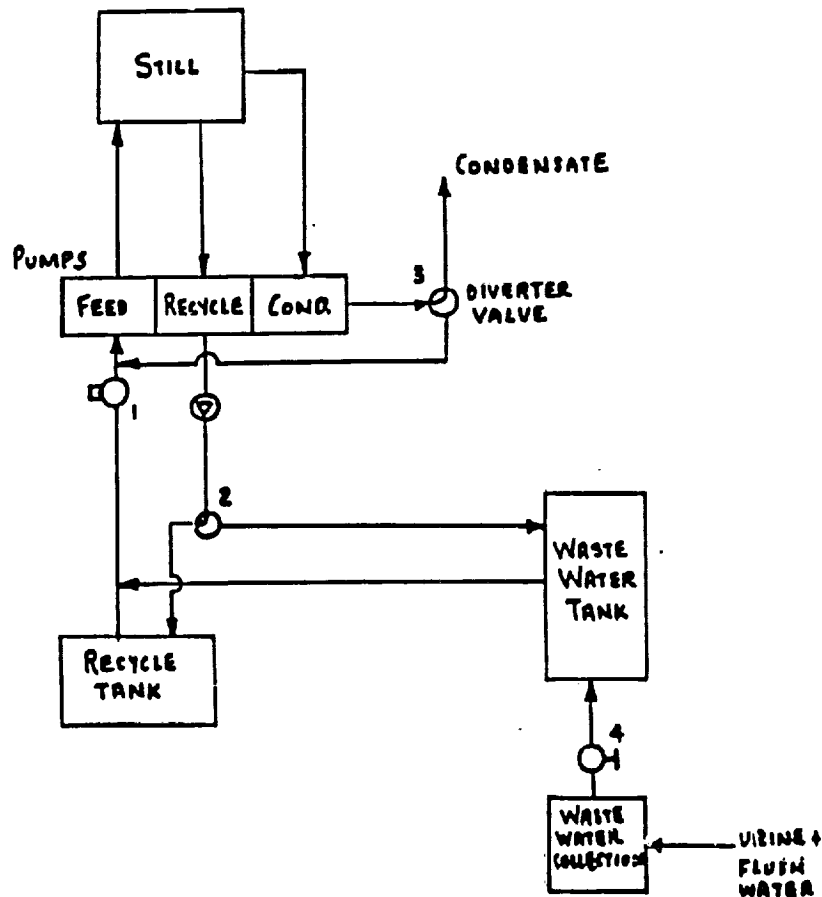


Figure 10 : Schematic of VCD (Adapted from design proposed by Lockheed INC)

The ASPEN model of the VCD is shown in Figure 11. The evaporator and the condenser are modeled as a combined unit using a SEP block. This is valid because there is no heat exchange from the environment for the combined unit. Since ASPEN can only model a steady state process, we have assumed that a 50% concentrated brine is obtained from the evaporator. This eliminates the presence of a recycle loop. This model predicts a 99.8% recovery of waste water which is greater than the literature values of 96%, (Schubert, 1983).

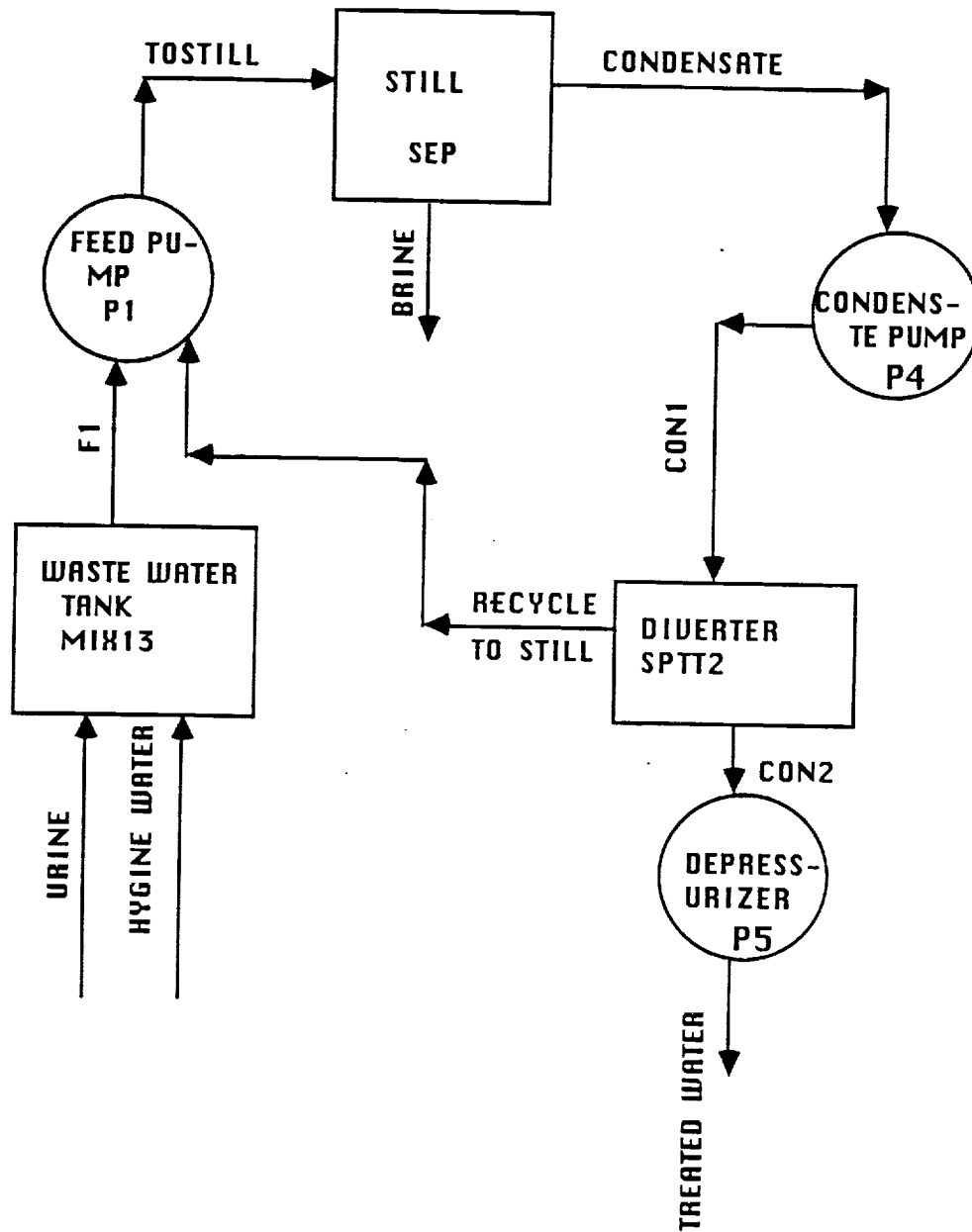


Figure 11 : ASPEN model of VCD

Thermo electric Integrated Membrane Evaporator Subsystem (TIMES)

Process Description (Winkler, 1982) :

The TIMES is a vacuum distillation subsystem that combines a hollow fiber membrane evaporator with a thermo electric heat pump.

The waste water is first pretreated with sulfuric acid/chromium trioxide solution to provide bacteria control. It is then heated to near the pastuerization temperature of 150 °F by a heat exchanger in contact with the hot junction surfaces of a thermo electric heat pump. The heated waste water then passes through a tubular hollow fiber membrane evaporator. The outside surface of the membrane tubes are exposed to a low pressure of 2.47 psia. Water diffuses through the tube walls and evaporates, forming steam at the tube outer surface while other liquid and dissolved solid constituents of the waste water remain in the recycle loop. The slightly cooled and concentrated waste water is then returned to the recycle tank. The solids concentration in the recycle loop gradually increases until a solids concentration of around 40% is reached. At this point the process is stopped, and the recycle tank and the filter are removed using maintenance probes. Fresh recycle tank and filter units are installed and the process is continued.

Evaporated steam is condensed to water on a chilled porous plate surface that thermally contacts the cold junction surface of the thermo electric heat pump. The condensate is then drawn into an accumulator. Figure 12 shows the schematic of the process.

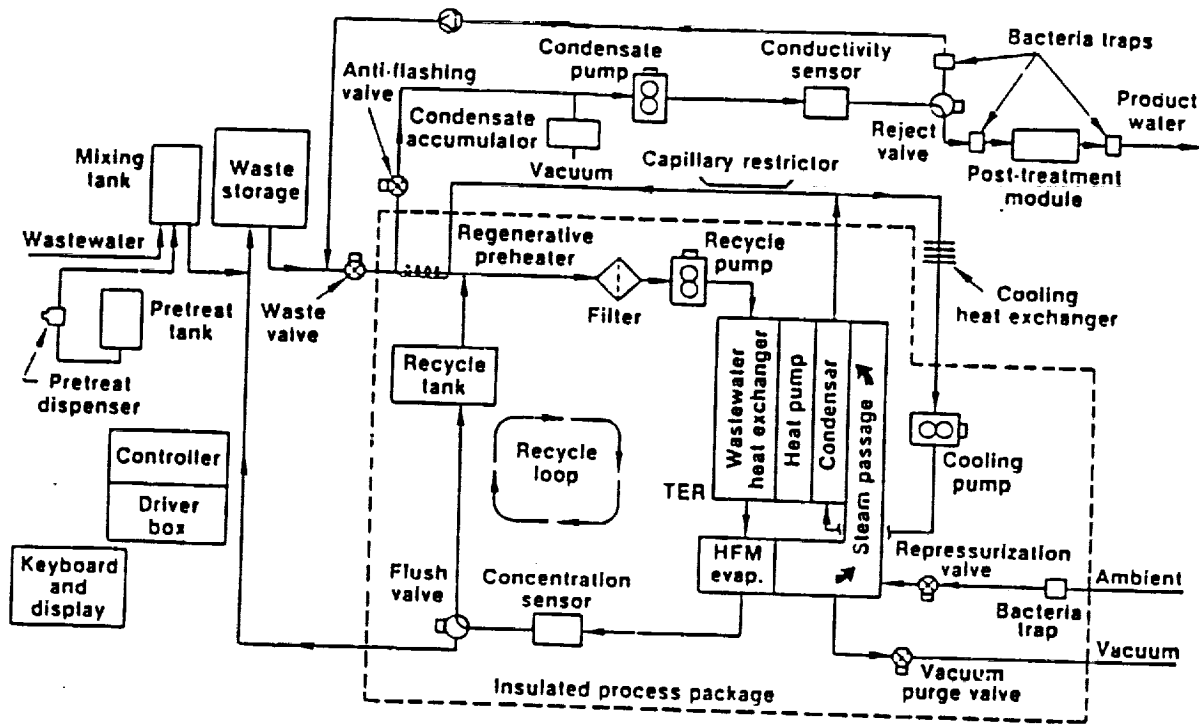


Figure 12: Schematic of TIMES (Adapted from Winkler et al., 1982)

The ASPEN model of the process is shown in Figure 13. Our approach here is to model the nature of the operation of TIMES, not the actual unit operation blocks involved. The thermo electric junction is modeled using two heaters, one for the hot junction and the other for the cold junction with heat being transferred from the hot to the cold junction. Since ASPEN has no tailor made blocks to model membrane separation we use a SEP block to simulate the operation of the membrane separator. The steam leaving the evaporator is saturated at the evaporator temperature. From the steam tables the saturation pressure of the steam is 3.784 psia. For the purpose

of developing a steady state model we assume that the brine from the evaporator is 40% concentrated with solids and that there are no recycle loops. Predicted recovery of waste water from our simulation calculation is 99.7%.

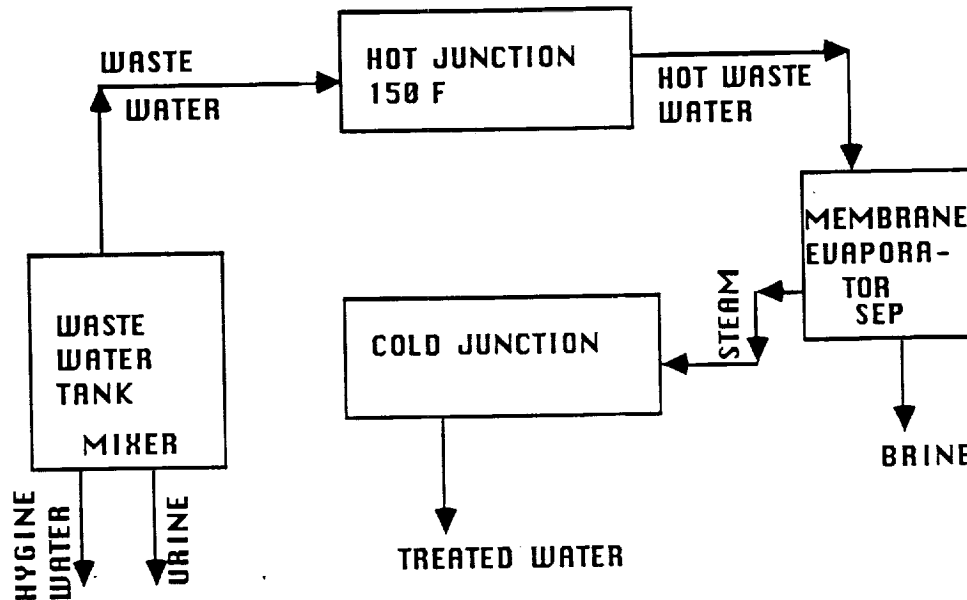


Figure 13 : ASPEN model of TIMES

Air Revitalization System

The air revitalization system (ARS) is a critical component of the life support structure on a spacecraft or a planetary base. The ARS controls the temperature, pressure and composition of the cabin. The subsystems included in the ARS are Trace Contaminant Removal, Humidity Control, CO₂ removal and reduction and N₂ and O₂ production, storage and distribution. Different modules are available for each subsystem. We shall now give a brief outline of the process schematic of each module followed by its ASPEN model.

Trace Contaminant Removal Subsystem

Contaminants in a manned space craft emanate from both the crew and the equipment. As mission durations, vehicle sizes, crew sizes, vehicle payload and experimental complexities increase and as the space craft leak rates decrease there will be a concomitant increase in the concentration of the trace stream. For our modeling purpose the flow rate of the contaminant stream was multiplied by the size of the crew. The following technologies are available for contaminant removal , (Ammann , 1989) :

- condensing heat exchanger
- freeze out
- decomposition by corona discharge
- adsorption on molecular sieves
- catalytic oxidation
- chemisorption

Table 2 shows the generation rates of the different trace stream components. This is based on a basis of 1 crew member.

Table 2 Composition of Trace Contaminant Stream (Adapted from Ammann,1989)

Component	G [mg/day]
CO	3000
CH ₄	300
C ₂ H ₆	2
C ₂ H ₄	0.05
C ₂ H ₂	0.5
H ₂	260

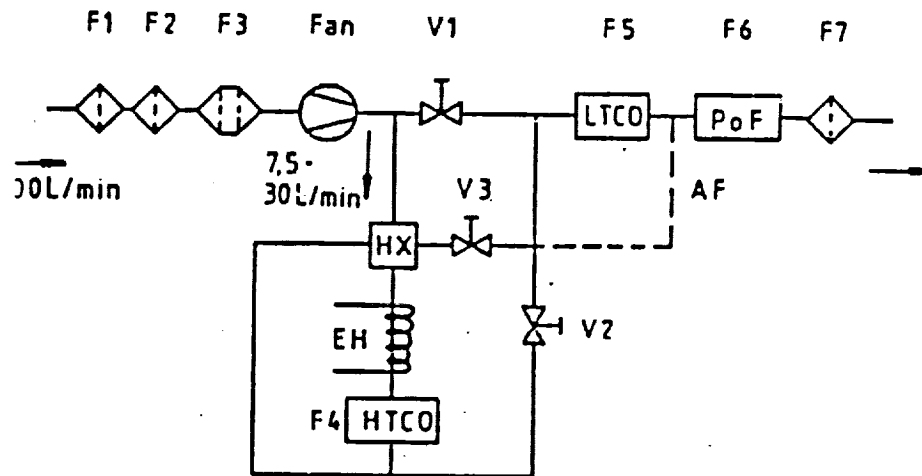
For our study the catalytic oxidation process was chosen.

Catalytic Oxidation Process

Process Description :

Figure 14 shows a schematic of the process. The process air initially passes through a pre filter which removes the harmful substances present like ammonia or freon which act as catalyst poisons. The bulk of air then flows into the LTCO (Low Temperature Catalytic Oxidizer) which operates at ambient temperature. The CO is oxidized in the LTCO. A small portion of the air which is adjustable, depending on the CH₄ concentration (i.e higher the CH₄ concentration the greater the flow rate) flows into the HTCO (High Temperature Catalytic Oxidizer). Prior to entering the HTCO, the bypass flow passes through a heat exchanger (HX) and an electrical heater (EH). The temperature to be maintained in the HTCO is between 400 - 450°C. In the HTCO all the higher hydrocarbons present in the trace gas are oxidized. The

recombined flow from the HTCO and the LTCO leaves via a post filter, the purpose of which is to adsorb the acid decomposition products which are generated by catalyst contact and the outlet particle filter.



- F1 Prefilter Module 1/(Charcoal filter CCF)
- F2 Prefilter Module 2/(Charcoal filter CCF)
- F3 Prefilter Module 3/(Charcoal filter CCF with Particle Filter PF1)
- V1-V3 Valves
- HX Heat Exchanger
- EH Electrical Heater
- F4 High Temperature Catalytic Oxidizer
- F5 Low Temperature Catalytic Oxidizer
- F6 Postfilter
- F7 Outlet Particle Filter (PF2)
- AF Alternative Feedback of HTCO By-Pass

Figure 14: Schematic of the Catalytic Oxidizer Process (Adapted from Ammann,1989)

The ASPEN model of the Catalytic Oxidation technology is shown in Figure 15. A user written Fortran block is used to determine the split fraction of gas going into the HTCO. The split fraction depends on the CH_4 concentration in the feed and varies from 0.075 to 0.3. The two reactors were modeled using RGIBBS, which calculates reaction equilibrium based on Gibbs energy minimization.

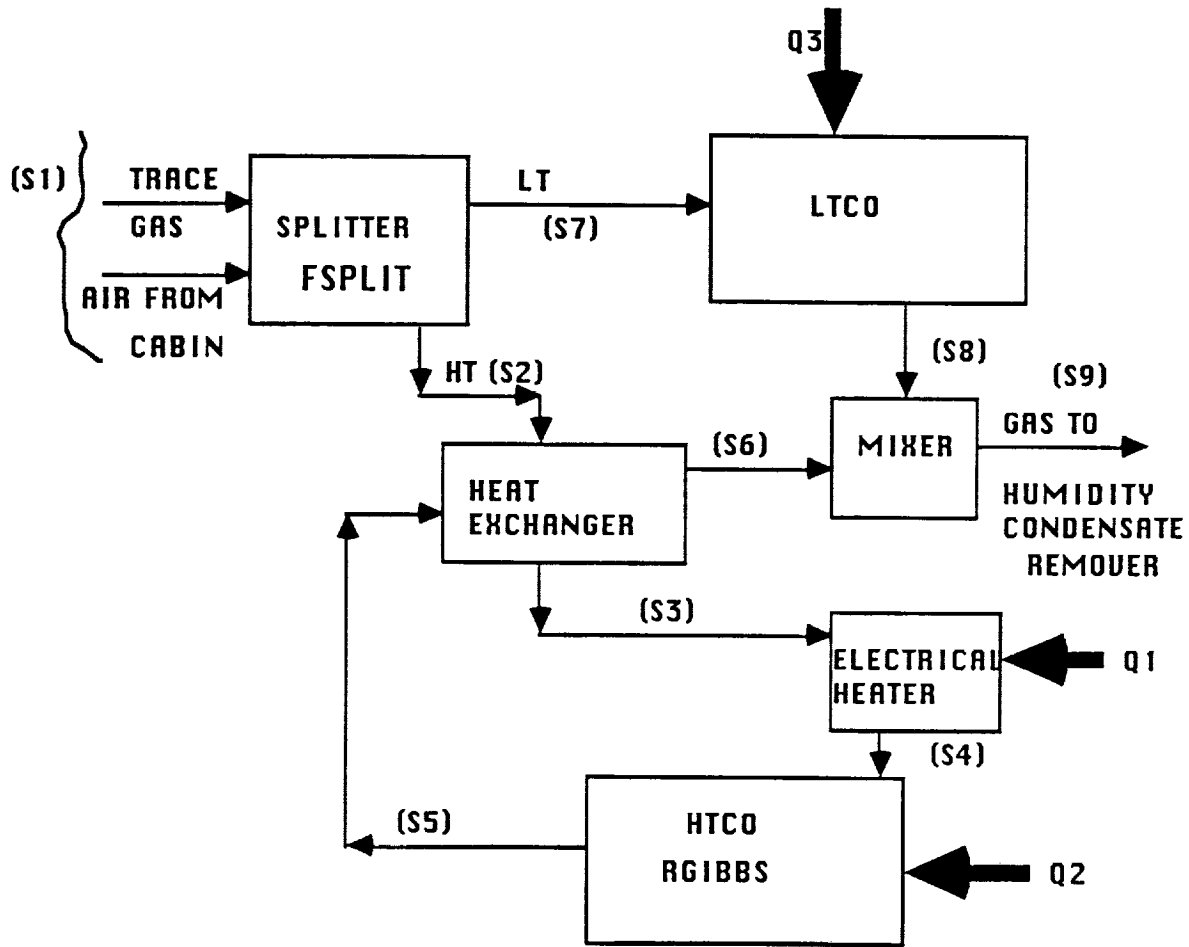


Figure 15: ASPEN model of the Catalytic Oxidizer Process

Atmosphere Humidity Control

The temperature and humidity of a habitat is to be regulated in order to provide a comfortable working environment. For our model we used a condenser-separator module to control the cabin humidity level. Our goal is to cool the gas from the trace removal subsystem to a temperature such that amount of water vapor in the exiting gas is equal to the amount of water vapor which is to be supplied to the cabin to maintain the cabin humidity level. The condensate is treated to obtain water of potable quality. The absolute humidity (mass of water/ mass of dry air) is thus known.

Determination of the temperature of the condenser involves an iterative technique, which involves reading enthalpy values of the gas and liquid water from psychometric charts.

This technique cannot be easily adopted for modeling purpose. For our modeling purpose we assume that the gas leaving the condenser is saturated with its moisture content. The temperature of the exiting gas is given by the following relation, (Treybal, 1988) :

$$t_{G2} = t_{G1} - \frac{\lambda}{C_s} (Y_{in} - Y_{out}) \quad (28)$$

where

t_{G2} temperature of outgoing gas from condenser

t_{G1} temperature of incoming gas to condenser

λ latent heat of vaporization 1075.8 Btu/lb

C_s humid heat

$$= 0.24 + 0.45 Y_{in} \text{ Btu/l(lb of air).}^{\circ}\text{F}$$

Y_{in} absolute humidity of gas in

Y_{out} absolute humidity of gas out

For the ASPEN model the condenser and the separator is modeled as a single unit using a SEP block. Knowing the absolute humidity of outgoing air the split fraction of the SEP block is determined in a user written FORTRAN block. Likewise, the temperature of the outgoing air is also determined using relation (28). A provision has however been provided for in the FORTRAN block that if the required temperature of the condenser falls below 40°F, the condenser temperature is to be set to 40°F. This option is provided to conserve energy.

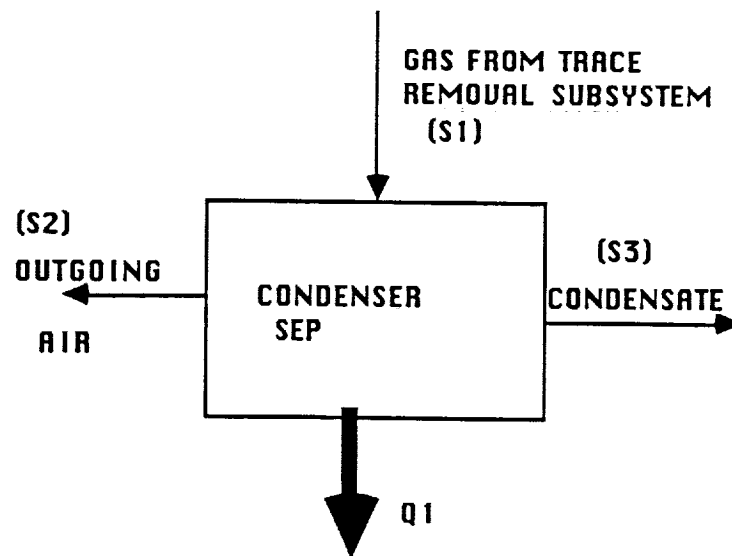


Figure 16: ASPEN model of Humidity Condensate Removal.

Carbon dioxide Removal Subsystem

According to the NASA requirement, in order to maintain comfortable living conditions in the crewed habitat the partial pressure of CO₂ must not exceed 3mm Hg, (Ray et al., 1987). In order to achieve this requirement the excess CO₂ in the air (generated due to food metabolism and in the trace removal subsystem) is removed in the CO₂ removal subsystem. The CO₂ that is removed is concentrated and then sent to the CO₂ reduction subsystem.

The commonly used CO₂ removal subsystems are :

- Solid-Amine Water desorbed CO₂ concentrator
- Electrochemical depolarized CO₂ concentrator
- 2 or 4 - Bed Molecular seive
- Metal oxide process where the CO₂ is complexed with a solid metal oxide
- Liquid - Sorbent / Membrane - Contactor system

For our study the Liquid - Sorbent / Membrane - Contactor system was chosen. The reasons for choosing this system are :

- light weight
- requires no consumables or expendables
- simple and does not rely on other ECLSS subsystems

Process Description (Mc Cray et al., 1990) :

CO₂ rich air is circulated through one side of the hollow-fiber membrane contactor and CO₂ is absorbed into the liquid sorbent, which is circulated on the other side of the membrane contactor. The CO₂ rich liquid sorbent is then sent to the second hollow fiber membrane contactor, where the CO₂ is removed using a vacuum compressor. The regenerated sorbent is then recycled to the absorption membrane contactor. A schematic of this process is shown in Figure 17.

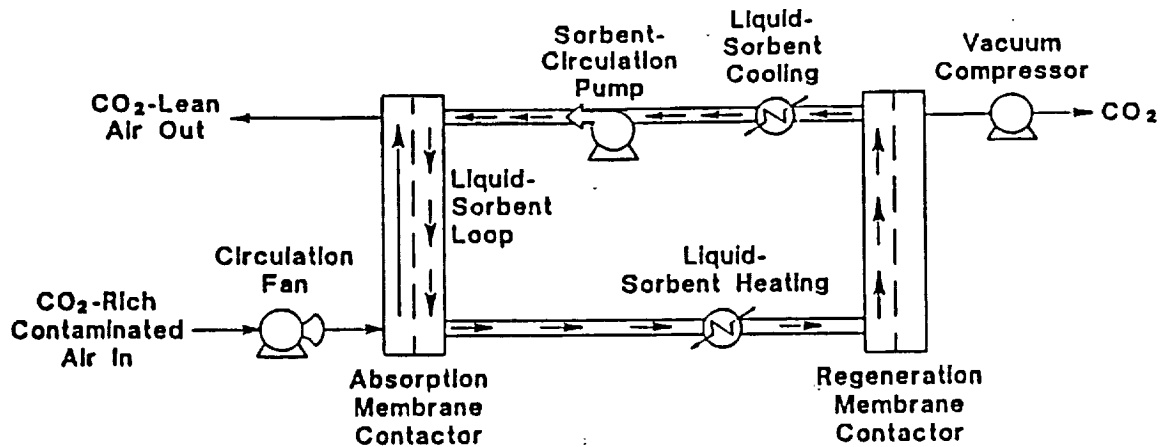


Figure 17: Schematic of Membrane based CO₂ removal system (Adapted from Ray et al., 1990)

There being no tailor made blocks for membrane separators in ASPEN, our goal was to model the process objective rather than the actual unit operation. This was

accomplished by the use of a SEP block. The SEP block removes the CO₂ from the air which is in excess of the amount to be present in the cabin air in order to satisfy the cabin atmosphere requirements of 0.3% CO₂. The separation degree of the SEP block is regulated by a user incorporated Fortran block. The air is cooled to 69°F before being sent to the cabin. The CO₂ is sent to the CO₂ reduction subsystem.

Carbon dioxide Reduction Subsystem

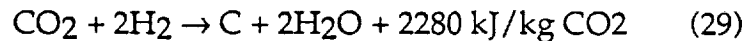
Among several technologies known for reducing CO₂, the Sabatier and Bosch process are the two primary options being considered for application in a regenerable ECLSS. Both process reduce CO₂ by catalytic reaction with hydrogen. The Bosch process produces carbon and water while the Sabatier process produces methane and water. Following is a brief discussion of each of these processes.

Bosch CO₂ reduction

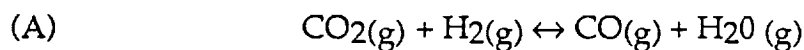
Detailed description of the Bosch process, its operation, specific hardware and performance are discussed extensively in the literature (Holmes, King and Keller, 1973, King and Holmes, 1976, Schubert, 1974, Manning and Reid, 1975). We shall give a brief summary of the process followed by its ASPEN model.

Process Description :

The Bosch reaction occurs at 800 to 1000K (980 to 1340 °F) in the presence of various catalyst such as iron, cobalt, nickel or ruthenium/iron alloys (Manning, Reid and Sophonpanich, 1982, Kolodney, Lange and Edeen, 1991). CO₂ combines with H₂ and produces carbon and water vapor as indicated in the overall reaction :



The reaction mechanism however involves several reactions :



- (B) $\text{CO(g)} + \text{H}_2\text{(g)} \leftrightarrow \text{C(s)} + \text{H}_2\text{O(g)}$
 (C) $2\text{CO(g)} \leftrightarrow \text{C(s)} + \text{CO}_2\text{(g)}$
 (D) $\text{C(s)} + 2\text{H}_2\text{(g)} \leftrightarrow \text{CH}_4\text{(g)}$

Reaction A occurs first, the others can then occur in parallel. Reaction (C) may not be significant but reaction D is, (Minemoto et al., 1989). However it has been shown that if two reactors are used in series one operating at a higher temperature than the other, the CH_4 concentration is negligible in all streams, (Minemoto et al., 1989). In practice, single pass efficiency through the bosch reactor is less than 10% for iron catalysts. Complete conversion is attained by recycling the processed gases with continuous deposition of carbon and removal of water vapor. Since all the reactants entering the subsystem are eventually converted to carbon and water, the overall stoichiometric ratio of two moles of H_2 to one mole of CO_2 must be maintained, (Spina and Lee, 1985). The schematic of the process is shown in Figure 18.

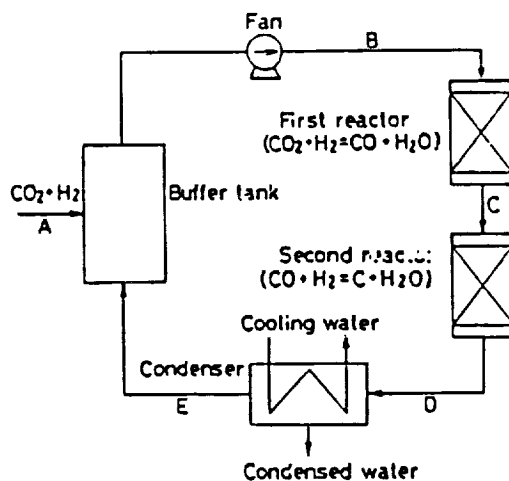


Figure 18: Schematic of Bosch process (Adapted from Minemoto et al., 1989)

The high purity CO_2 recovered by the CO_2 removal process and H_2 for the reduction are mixed, and this gas is taken to a buffer tank. Then the circulating fans channels the gas through the first and second reactors. The first reactor is maintained at a temperature of 1300 [K] while the other reactor is maintained at 900 [K]. In the first reactor reaction (A) occurs while reaction (B) is predominant in the second reactor. Methanation occurs to an appreciable limit in the second reactor. To prevent the accumulation of CH_4 within the subsystem which would eventually lead to a shut down of the process there is a bleed line connected to the trace removal subsystem. The solid carbon is collected in the second reactor, water vapor generated is condensed in the condenser and the unreacted gas is returned again to the buffer tank to be recycled again.

The reactors of the bosch system were modeled using the RGIBBS equilibrium reactor model. The validity in using RGIBBS is checked by estimating the conversion for a single pass (i.e no recycle). From the ASPEN model net conversion is found to be 37.6%. This is so because two reactors are used in series. Moreover in actual reactors 'graphite equilibrium' is usually not attained due to insufficient residence times and catalyst deactivation. Similar results were reported in literature, (Sacco and Reid,1978). In our model, the H_2 feed rate is determined in a user written Fortran block to ensure CO_2/H_2 stoichiometric ratio is satisfied. Figure 19 shows the ASPEN model of the Bosch system.

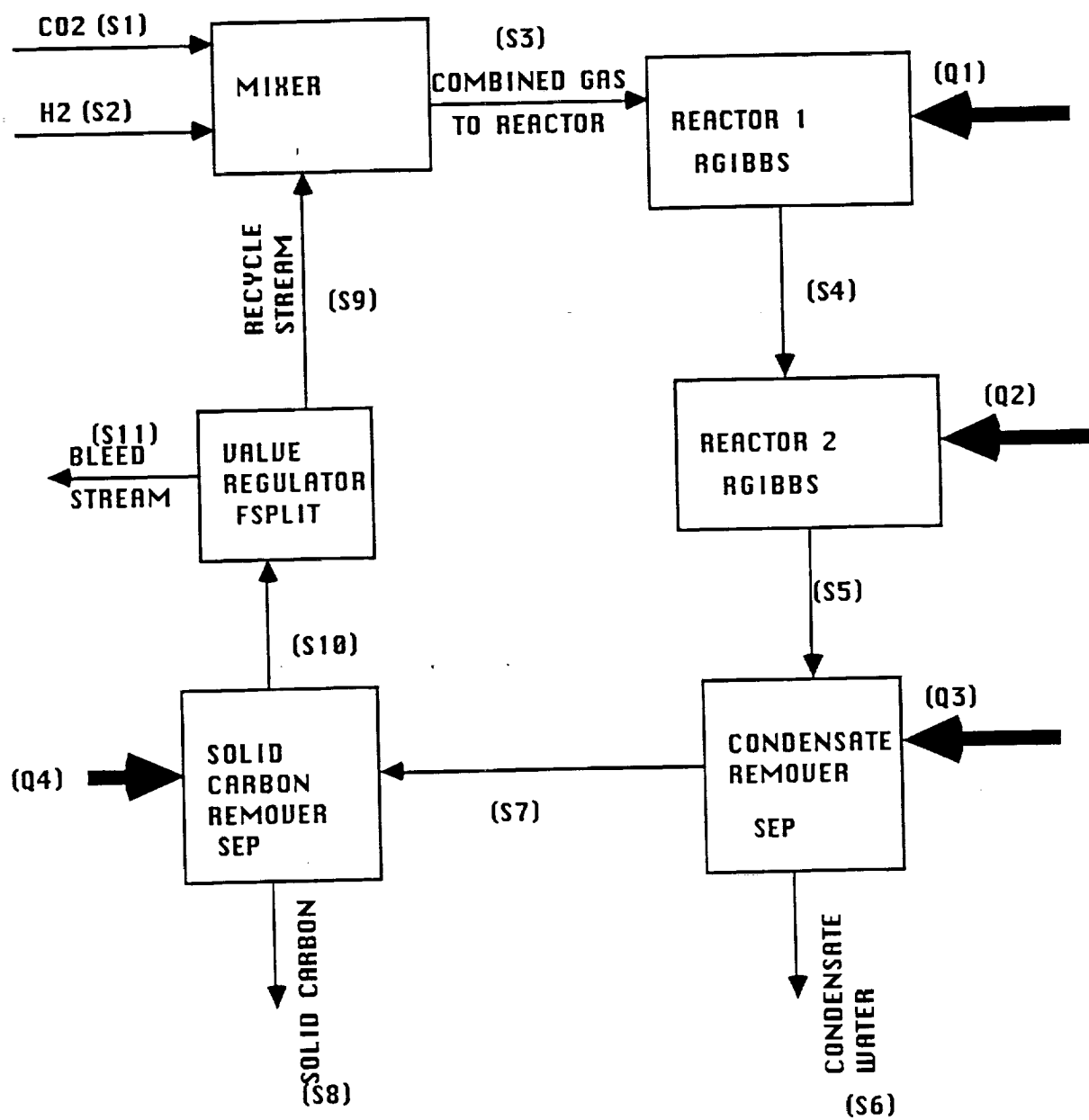
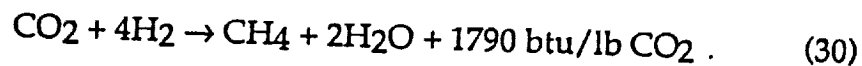


Figure 19: ASPEN model of Bosch system

Sabatier Reactor

Process Description:

The Sabatier reaction occurs at 350 to 980 °F in the presence of catalyst. The reaction mechanism is shown below



With a stoichiometric reactant mixture the reaction efficiencies are higher than 98%, (Spina and Lee, 1985). So a single pass is always used for a Sabatier reactor. The methane and water vapor formed along with the excess reactants are cooled in the condenser where the water is condensed. The remaining methane and other gases are directed to the trace removal subsystem. Figure 20 shows the system schematic.

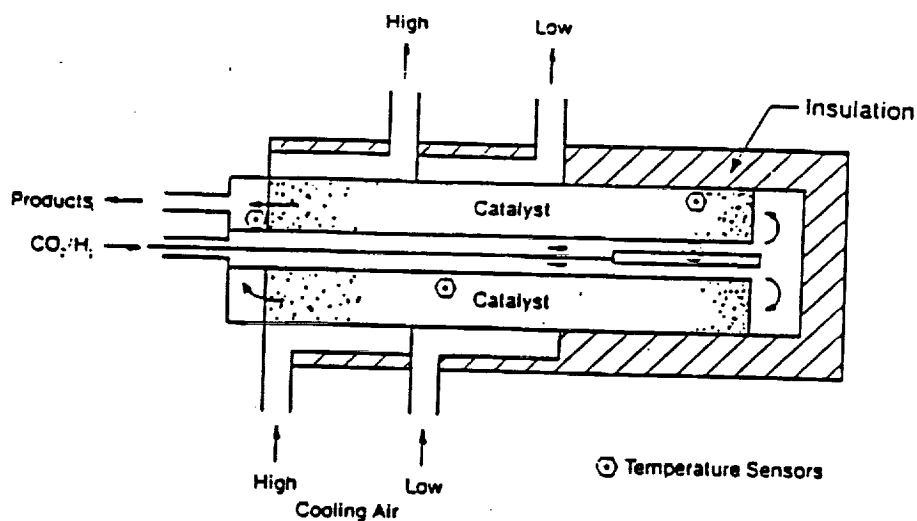


Figure 20 : Functional schematic of the Sabatier (Adapted from Spina and Lee, 1985)

The ASPEN model of Sabatier is shown in Figure 21. The reactor is modeled using a RSTOIC. The reason for choosing RSTOIC is that since the conversion per

pass in the Sabatier reactor is usually higher than 98% , a RSTOIC with a specified conversion of carbon dioxide of 98% can adequately simulate the real process. A user written Fortran block is incorporated to direct the stoichiometric amount of H_2 to the reactor.

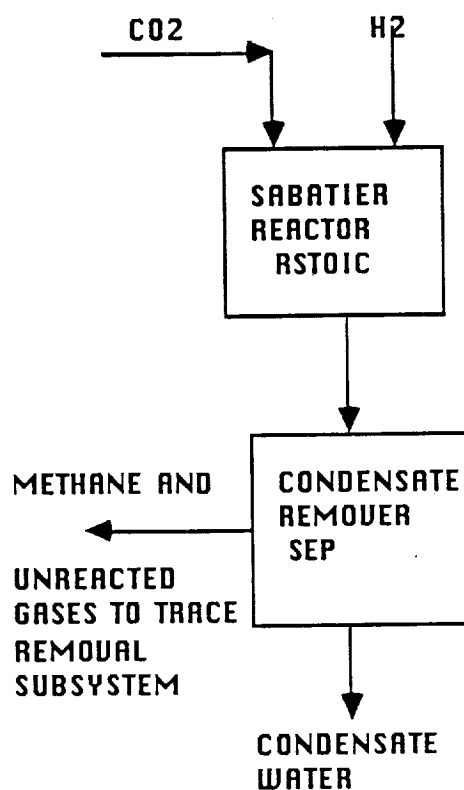


Figure 21: ASPEN model of the Sabatier

Oxygen generation subsystem

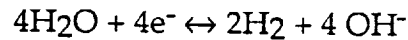
To meet the needs of the crew on board the space station O_2 and H_2 are to be supplied by an O_2 generation assembly. Apart from metabolic consumption, O_2 is required to make up for cabin leakage as well as air lock losses. H_2 is required for

CO₂ reduction. For our study we have chosen the **Static Feed Water Electrolysis system**.

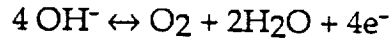
Electrolysis Process :

In a water electrolysis cell, water is dissociated into its elements by supplying electrons to a negatively charged electrode (cathode) to produce H₂ and removing electrons from a positively charged electrode (anode) to produce O₂. The half-cell reactions for the water electrolysis cells using an alkaline electrolyte are shown below : (Fortunato et al., 1988)

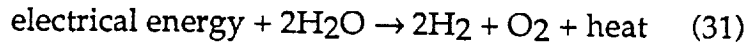
At the cathode :



At the anode :



Overall reaction :



Static Feed Water Electrolysis

Process Description :

Initially the feed water compartment is filled with water and the electrolyte retention matrix is fully charged with aqueous electrolyte. As electrical power is supplied to the electrodes, water is electrolyzed from the electrolyte retention matrix. This increases the initial electrolyte concentration gradient between the water in the feed water compartment and the electrolyte in the electrolyte retention matrix. Water vapor then diffuses from the water feed membrane into the electrolyte retention matrix due to this gradient. Advantages of this system are :

- since there is no contact between the liquid feed water and the cell electrodes ultrapure water need not be used.

- the water feed membrane is liquid impermeable but water vapor and gas permeable eliminates any concerns regarding H₂ diffusion into the water cavity.
- no dynamic phase pump/separators are needed to remove the product gas from the feed water stream.

Table 3 shows the design requirements for the process.

Table 3 Performance Requirements of Static Feed Water Electrolysis unit
(Adapted from Fortunato et al., 1988)

Parameter	Units	Operational mode
		H ₂
/O ₂ partial pressure	psia	2.83 - 3.35
O ₂ delivery pressure	psia	20± 5
H ₂ delivery pressure	psia	25± 5
H ₂ O supply temperature	F	65 - 80
H ₂ O supply pressure	psia	30 - 45

Schematic of the Static Feed Water Electrolysis process is shown in Figure 22.

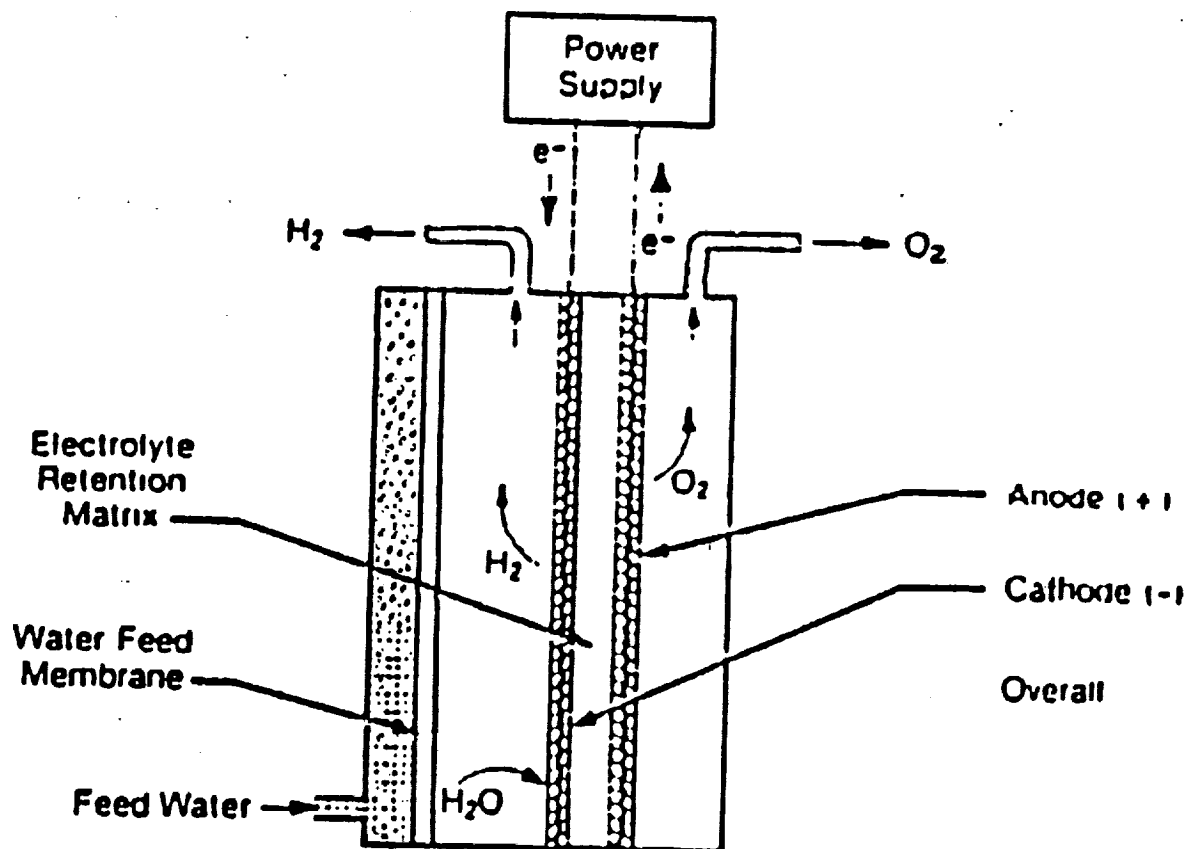


Figure 22 : Schematic of the Static Feed water Electrolysis process (Adapted from Fortunato et al., 1988)

For the ASPEN model of the Static Feed Electrolysis, the water from the water regeneration subsystem is pressurized to 30 psia before being fed to the water electrolyzer. A cooler placed before the electrolyzer removes the heat generated due to compression in order to supply water to the cell at the ambient temperature. Since ASPEN does not have any blocks to simulate the electrolysis process the overall process was modeled as a chemical reaction using a RSTOIC block with the reaction stoichiometry specified and the conversion of water set at 100%. The output from the electrolyzer is then sent to a SEP block which is a combination of a cooler, a depressuriser and a condenser. H_2 and O_2 are sent to their respective buffers. The ASPEN model of this process is shown in Figure 23.

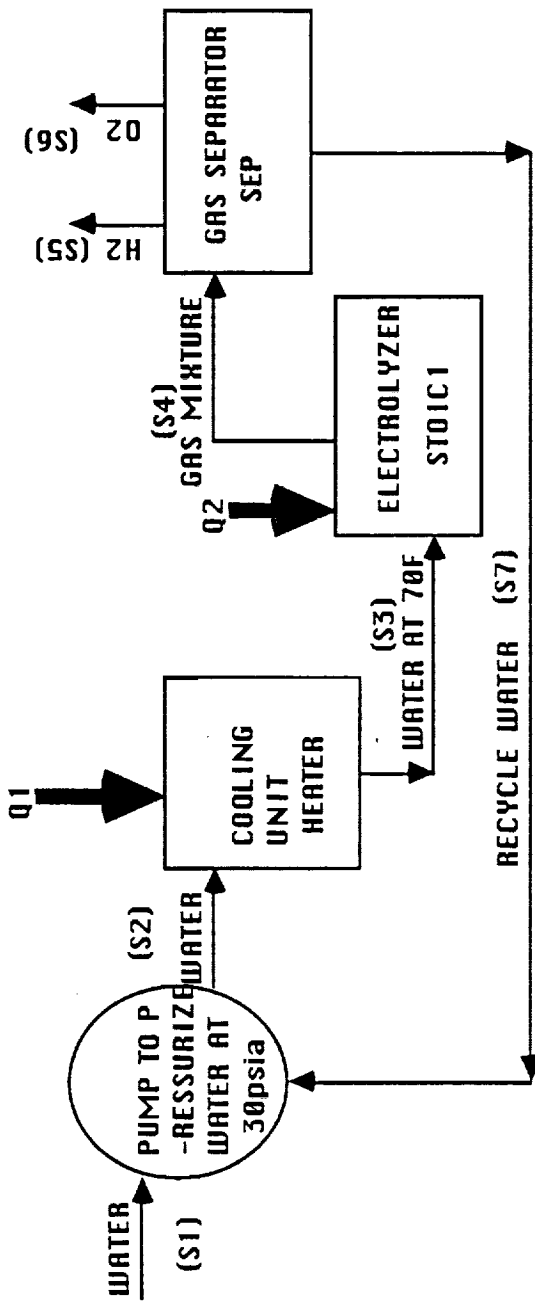


Figure 23: ASPEN model of Static feed water electrolysis

Solid Waste Management

Waste management is required to control the accumulation of materials that would otherwise lead to breakdown of the life support system. Apart from solid wastes generated by the crew, the other physico - chemical processes which constitute the life support system generate typical solid wastes which include particle filters, product carbon catridges, depleted catalysts, contaminated adsorbents, wate filters, wicking units, chemical and multifiltration units. Various technologies which can be used for solid waste treatment range from use of chemical germicides to stabilize fecal bacterial gas production to complete oxidation of organic wastes, (Quattrone, 1981). Again there are two types of oxidation :wet oxidation and dry oxidation (incineration). For our modeling purpose we used the wet oxidation process.

Wet oxidation Process

Process Schematic, (Takahashi and Ohya, 1985) :

Wet oxidation is a reaction in which organic or reductive compounds are oxidized in the presence of liquid water. This reaction occurs between 100 and 374 °C which is the critical temperature of water. The reaction is carried out in an autoclave to prevent evaporation of water. The pressure is set to 1067 psia. The added O₂ index is maintained at 1, i.e the exact quantity of O₂ is added to completely oxidize the raw materials. There is a linear relationship between % of carbon in waste and the temperature to be maintained in the oxidation process, (from Figure 1 of the paper by Takahashi and Ohya, 1985) . The linear relationship is :

$$\% \text{ of carbon in feed} = - 0.65 \text{ oxidation temp} + 194 \quad (31)$$

For the ASPEN model of the wet oxidation process, the oxidizer was modeled using a RSTOIC block. The temperature was determined from a user written Fortran block using the linear relationship of equation (31). We have assumed that only the carbon content of the waste is completely oxidized to CO_2 while the nitrogen and the hydrogen components of the feed remain unchanged. Thus the ECLSS loop is not completely closed as far as nitrogen and hydrogen are concerned, and a buffer must be used.

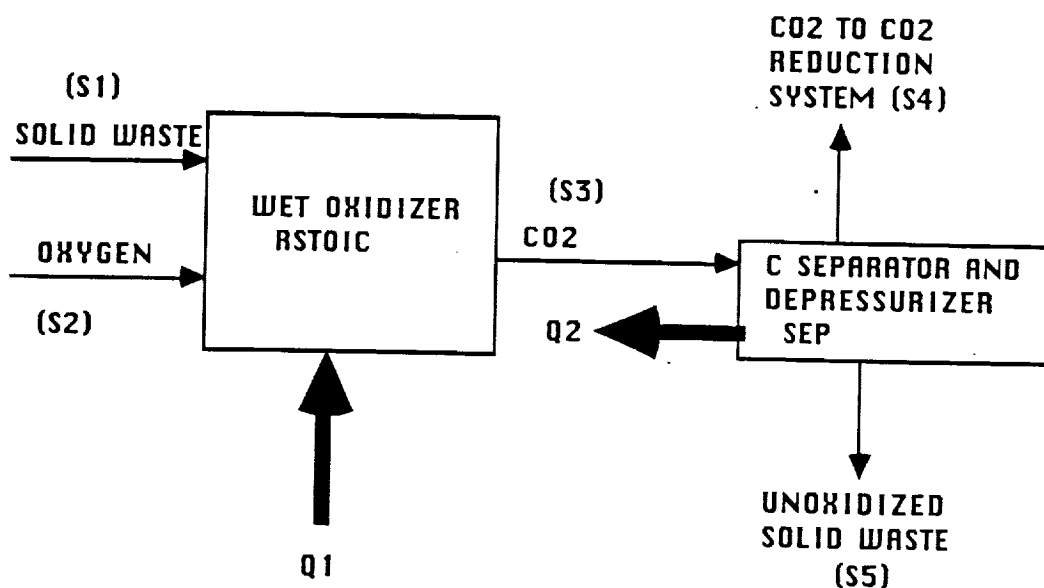


Figure 24: ASPEN model of the wet oxidation process

5 RESULTS AND DISCUSSIONS

In order to compare quantitatively the merits and demerits of storage vs regeneration of the critical constituents of a life support system (LSS) a detailed systems analysis is required. Herein, we present the results which were computed from the ASPEN model of the ECLSS, which give us a perspective of the requirements and design of the ECLSS. The results can be interpreted to arrive at three categories of information :

- Mass balance sensitivity of the ECLSS.
- Technology trade study
- Parameter sensitivity analysis

Development of the integrated ECLSS model

As elucidated in Chapter 3, the crew is the primary producer of wastes. These wastes serve as inputs to the different life support modules. Since the objective of a regeneration design is to reduce the amount of expendables supplied, the wastes are processed in different LSS modules before being recycled back.

The crew specification will then influence the mass flow rates of the different components within the ECLSS.

It is thus imperative to provide an interactive environment for the crew model to study the mass flux values of the critical components under different scenarios. This was arranged by allowing the input variables like crew number, age, gender, height, weight and activity levels to be read from a user supplied data file.

As mentioned in chapter 2, the ECLSS consists of seven subsystems. The ECLSS modules are not water tight compartments but are closely connected to each other. The gaseous constituents and the water balances interact as :

- CO₂ reduction generates water which is processed to potable water

standards

- The bleed stream from the CO₂ removal process is directed to the trace removal subsystem.
- Humidity condensate from the humidity condensate removal subsystem is treated to obtain potable water.
- Part of the treated hygiene water is further treated to obtain makeup potable water and the remaining water is sent to the oxygen generation subsystem.
- The H₂ and O₂ from the O₂ generation subsystem are stored in their respective buffers
- The H₂ for CO₂ reduction is obtained from the H₂ buffer while the O₂ required for makeup O₂ in the cabin and for solid waste treatment is drawn from the O₂ buffer.

Figure illustrating the interaction between the LSS modules and the crew is included in Appendix 2.

In order to develop a complete ECLSS model which takes into account the interaction between the respective ECLSS subsystems, the ASPEN models of the different ECLSS subsystems (which were developed in chapter 4) were unified in a program. The user written crew model was then appended to the main program. The code is included in Appendix 3.

Mass Balance Sensitivity of the ECLSS

The utility of the type of LSS configuration chosen for the mission (e.g open loop, partially closed loop, or completely closed loop) can be gauged by estimating the flow rates of the critical components. Figures 25A, 25B and 25C show the variation in mass flow rates for three cases where,

Case 1: Completely open loop.

Case 2: Partially closed loop. No O₂ generation and CO₂ reduction subsystems are present. Food is supplied.

Case 3: Completely closed loop, however food is supplied.

It is to be noted that all the values shown in Figures 25A, 25B and 25C are for the baseline case of one man operating at basal metabolic rate.

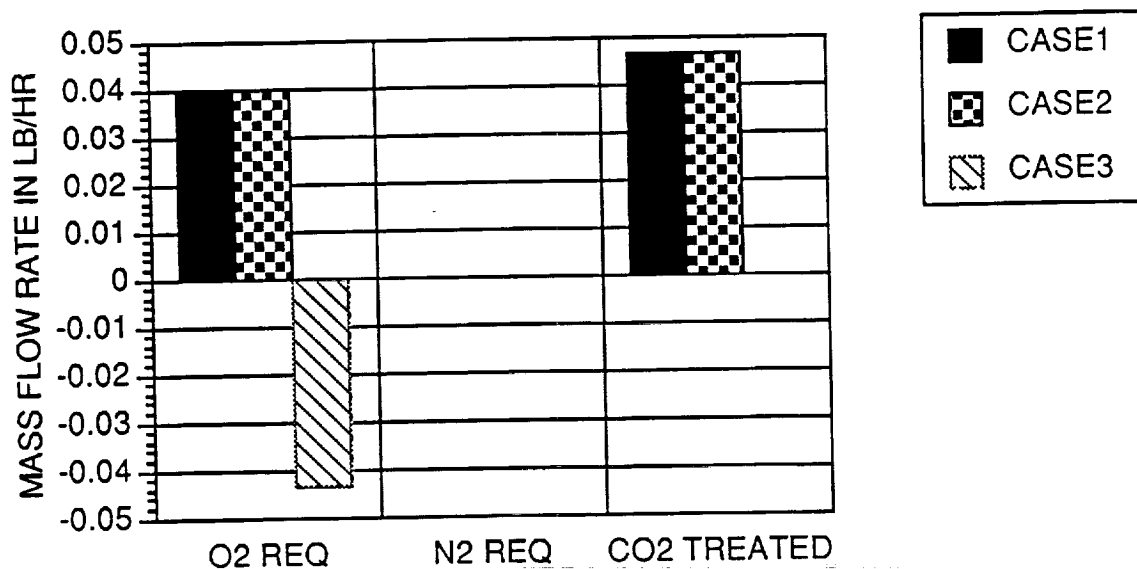


Figure 25A: O₂, N₂ and CO₂ requirement for the three cases.

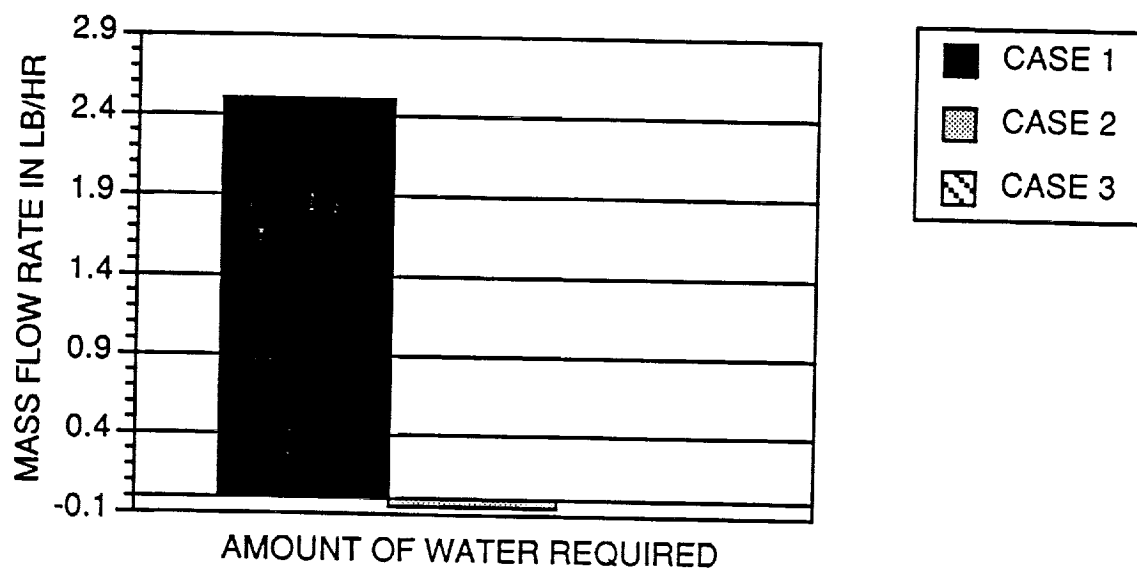


Figure 25B: Comparison of water requirement

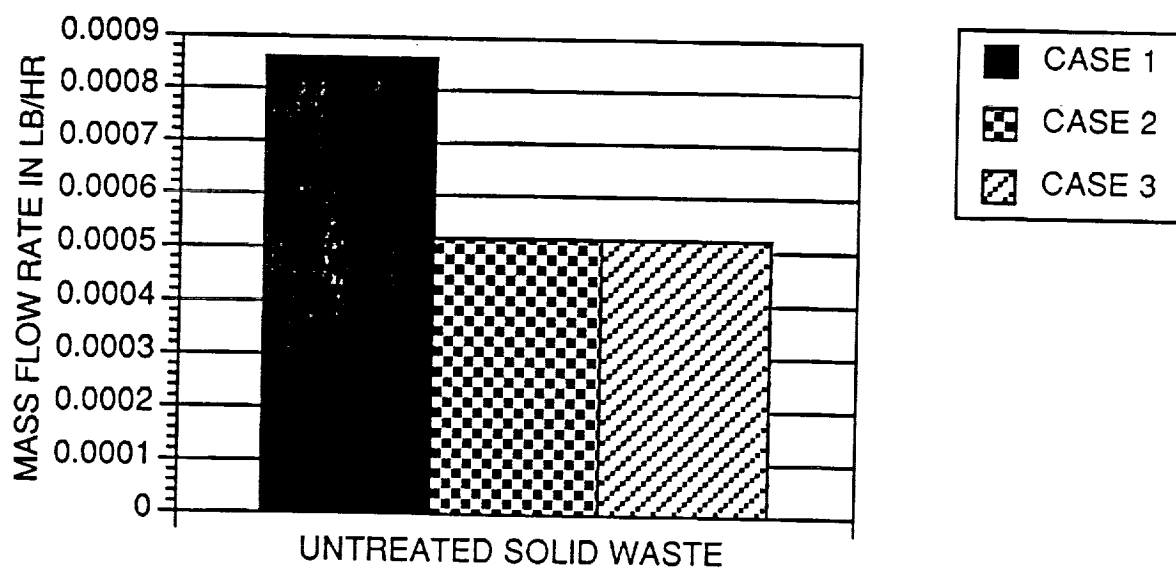


Figure 25C: Comparison of total untreated solid waste

It is observed from Figure 25A that with regard O₂ and CO₂ flow rates, the closed loop is advantageous to the other cases, as excess O₂ is produced which is stored in the buffer, and all the CO₂ which is produced is reduced within the system. The utility of the water regeneration subsystem is well illustrated in Figure 25B. The negative sign for the partially closed loop indicates that since there is no O₂ generation subsystem excess water is produced which is stored in the buffer. From Figure 25C it is evident that for a completely open loop the increase in amount of solid waste to be handled adds a greater burden to the system.

According to different crew missions the crew specification changes. Thereby, in order to arrive at a preliminary estimate of the sizing of the different ECLSS functional units and storage tank capacity, it is essential to know the mass-flow rates of the substreams within the ECLSS. Figures 26A, 26B and 26C show the variation in mass flow rates of the critical components with changing scenarios.

Case 1 : 1 man operating at basal metabolic rate

Case 2 : 1 man operating at 4 times the basal metabolic rate

Case 3: 1 man operating at 4 times basal metabolic rate and 1 woman operating at 3 times the basal metabolic rate.

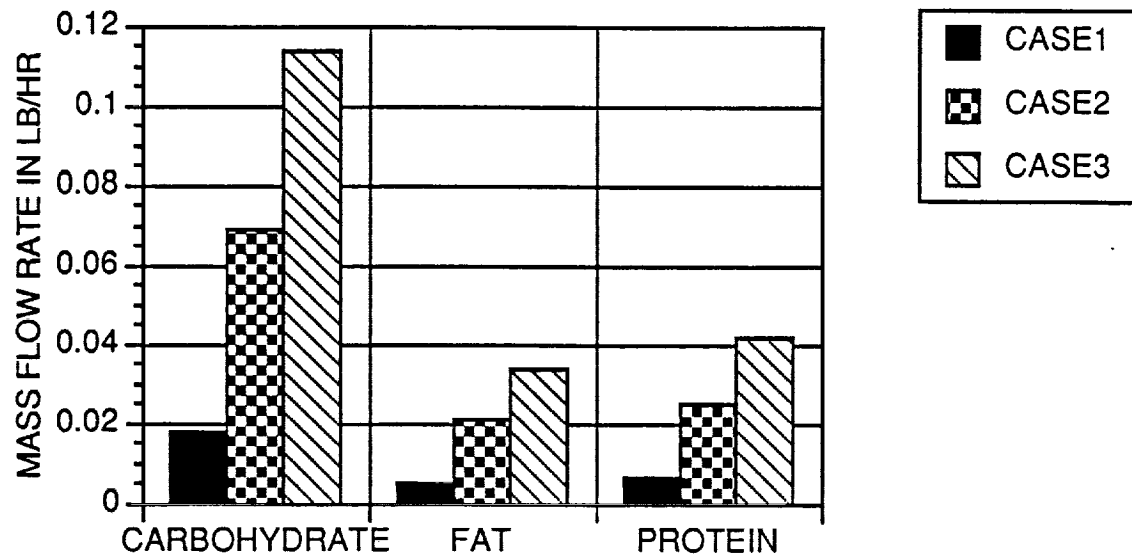


Figure 26A: Comparison of food requirement for the three cases.

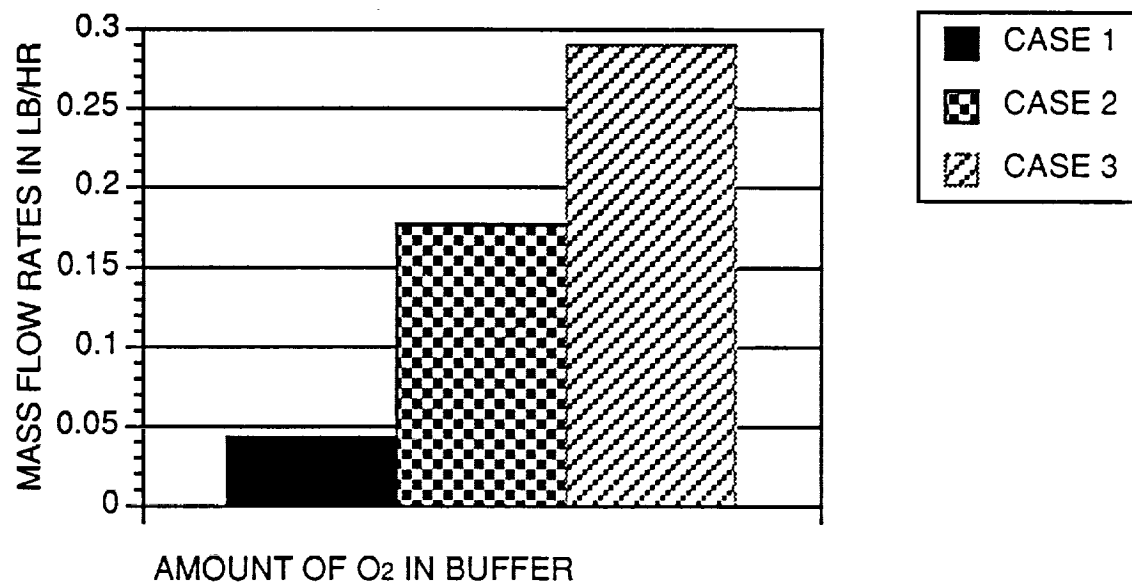


Figure 26B: Overall effect on the oxygen buffer for different crew scenarios

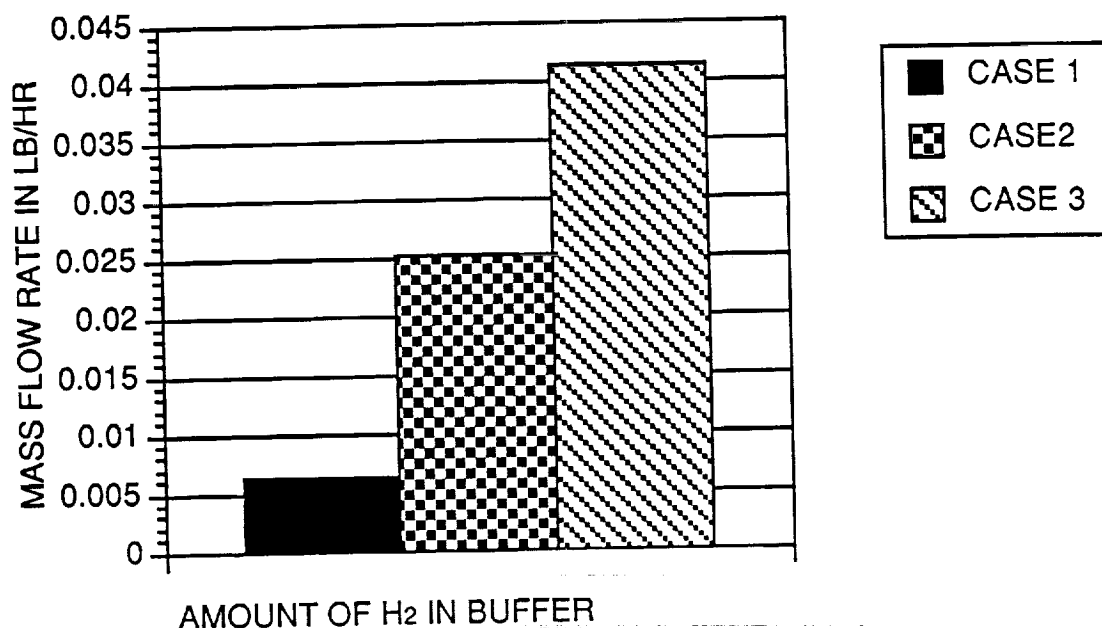


Figure 26C: Overall effect on the hydrogen buffer for different crew scenarios

Comparing Figures 26A, 26B and 26C we see that as the food consumption increases, the amount of O_2 and H_2 in the buffer increases. This is in accordance with the basic mass conservation law for a steady state system i.e the excess oxygen and hydrogen atoms which enter the system in the form of food eventually leave the system as gases which are then stored in the buffer.

Technology trade study

As outlined in chapter 4 each ECLSS subsystem can be modeled by a wide variety of candidate technologies. In order to choose the appropriate technology for the ECLSS configuration desired apart from knowing the subsystem efficiency, it is also essential to know how the introduction of the system affects the rest of the LSS.

Figures 27 and 28 show the comparison between competing technologies for water regeneration and CO₂ reduction respectively.

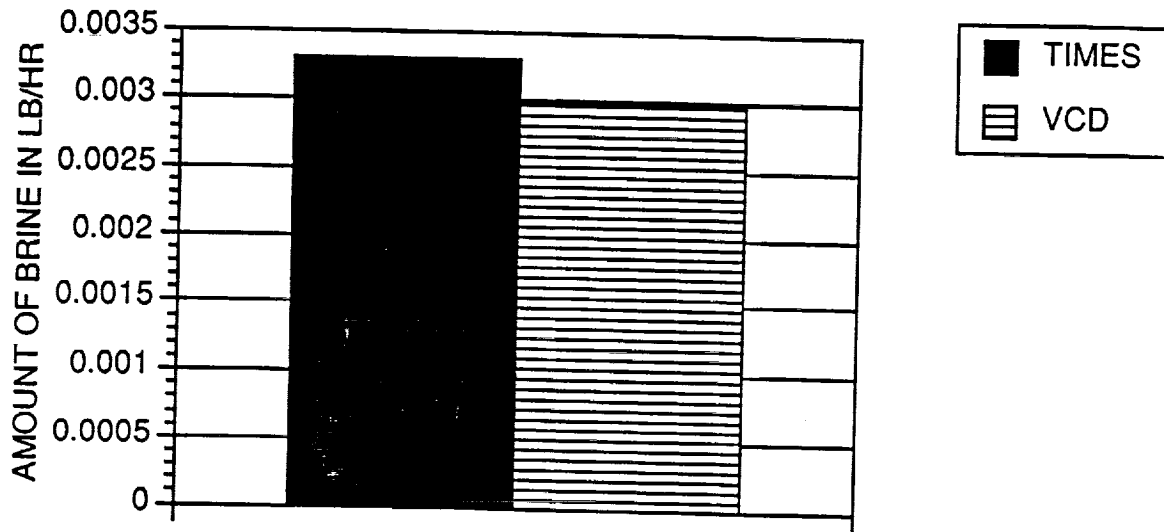


Figure 27A : Mass flow rates of brine from the VCD and TIMES.

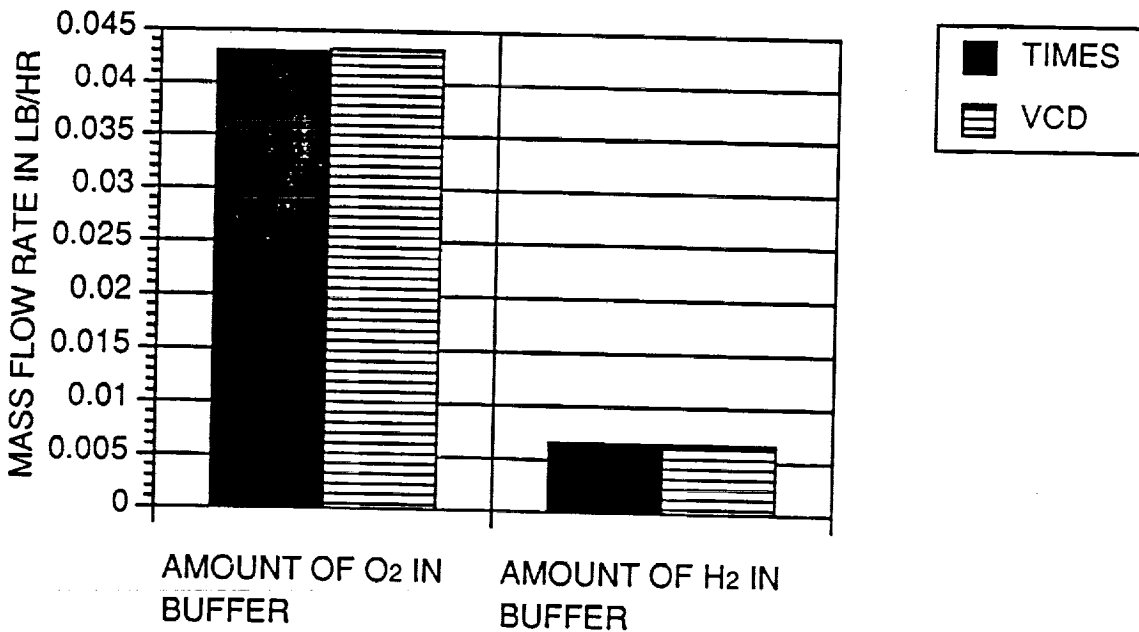


Figure 27B: Effect of VCD and TIMES on the overall system.

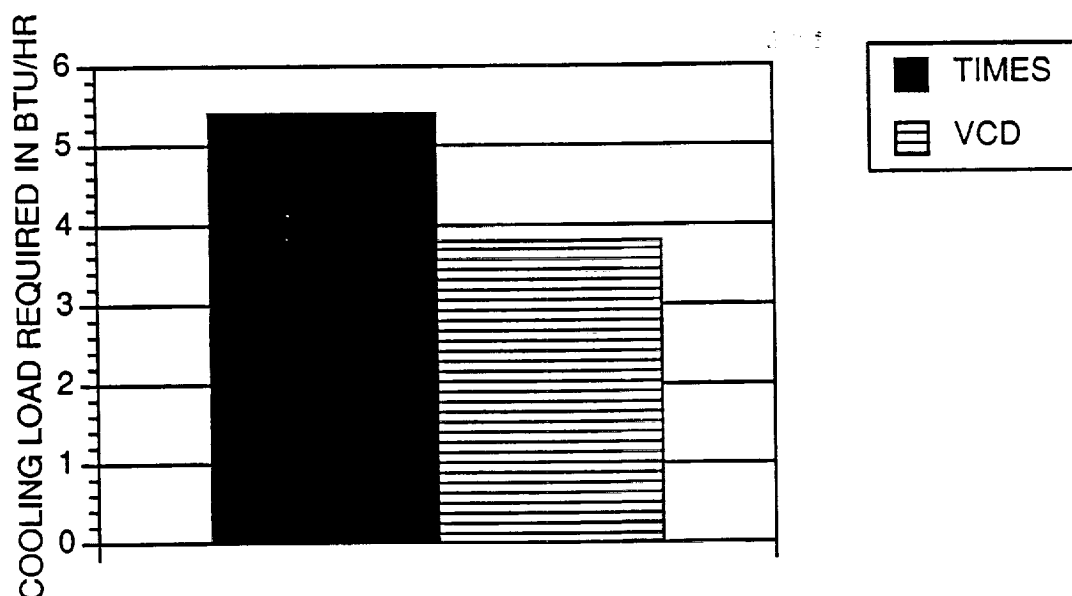


Figure 27 C: Comparison of cooling load required for the VCD and TIMES.

From Figures 27A, 27B, and 27C, we can deduce that VCD is more advantageous than TIMES, as:

- The cooling load required for VCD is lower than that required for TIMES. This is in accordance with the values reported in literature, which says that the TIMES requires twice the energy per pound of water produced compared to the VCD due to the inherent inefficiencies of the process, (Schubert,1983).
- More O_2 and H_2 is stored in the buffer when a VCD is used.
- Recovery efficiency of the VCD is greater than that of the TIMES. This is in agreement with the reported values of 96% recovery for the VCD and 92% for the TIMES, (Schubert,1983). The simulation values reported are however higher than the experimentally calculated values. This can be explained because for our simulation purpose we have assumed a steady state continuous process.

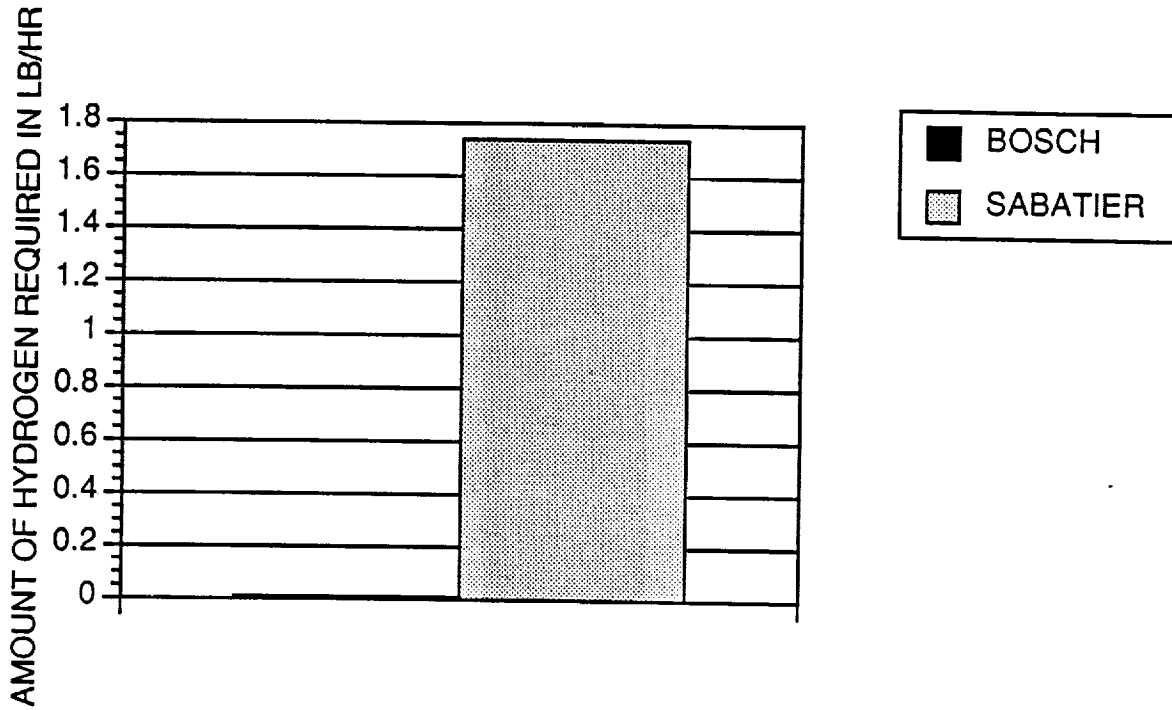
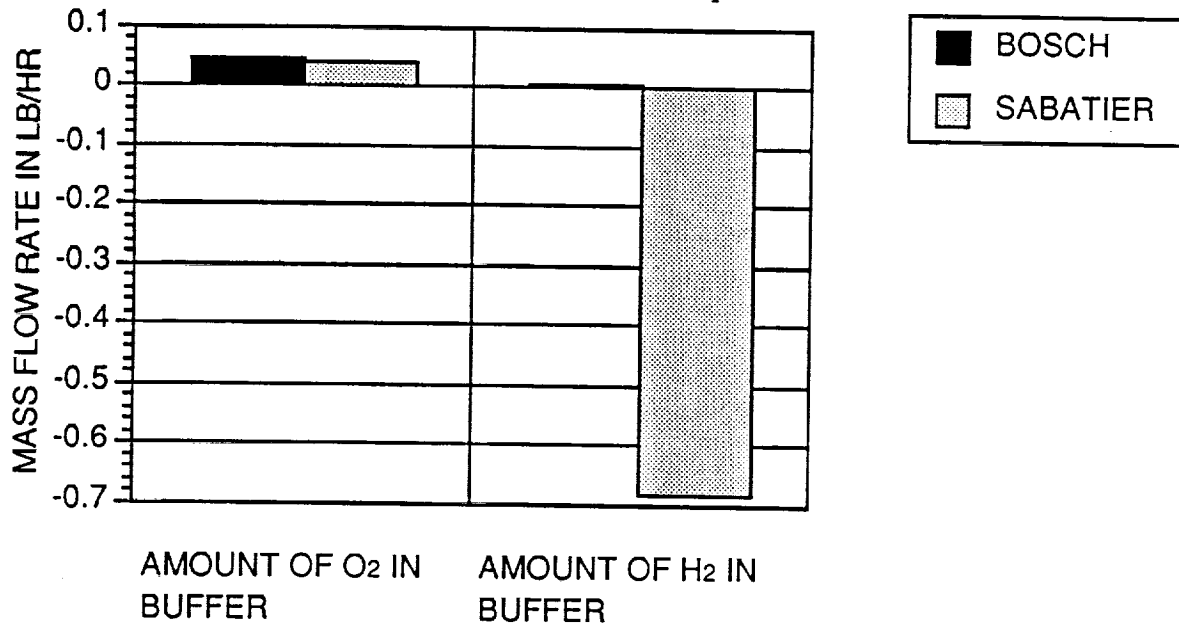


Figure 28A : Comparison of H_2 feed flow rate required for Bosch and Sabatier



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Figure 28B : Comparison of the overall effect on the entire system due to the presence of the Bosch or the Sabatier.

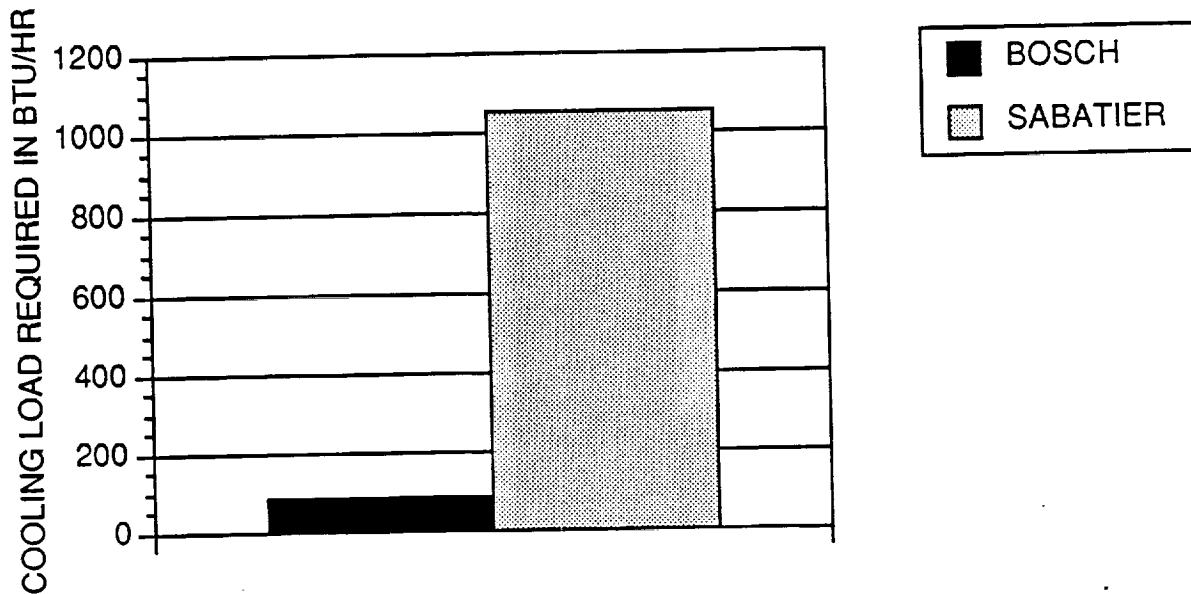


Figure 28C : Comparison of cooling load required for the Bosch and Sabatier

Similar to our deductions for VCD and TIMES from Figures 28A, 28B and 28C we can draw the analogy that the Bosch process is more advantageous as compared to the Sabatier process. This is substantiated by :

- The amount of H_2 required for the Sabatier being greater than the Bosch a continuous supply of H_2 is required to be supplied to the system for the operation of the Sabatier reactor. This is in agreement with the stoichiometric relation of the reactions taking place in the two reactors respectively.

- The amount of O_2 and H_2 stored in the buffer is greater when a Bosch reactor is used in place of a Sabatier reactor.

- The overall cooling load required is less for a Bosch as compared to a Sabatier. This is in apparent contradiction to the reported values in literature where the power requirement for a Bosch is 1.1 times that for the Sabatier, (Spina and Lee, 1985). This can be explained by considering that the amount of CO_2 to be treated for the basal case for the Bosch and Sabatier is 0.0465 and 0.4327 lb/hr respectively. This is so

because all the CH_4 formed in the Sabatier is oxidized in the Trace removal subsystem which adds an additional load to the CO_2 reduction subsystem.

Parameter sensitivity

The developed integrated model of the ECLSS can be used to study the performance criterion of the ECLSS functional units. Figure 29 shows the variation in performance of the Bosch reactor and its overall effect on the entire ECLSS as the mass ratio of the bleed stream from the Bosch to the Trace Removal system is varied from 0 to 1.0 as shown in the three cases, where :

Case 1 : Bleed fraction is 0.0

Case 2 : Bleed fraction is 0.5

Case 3 : Bleed fraction is 1.0

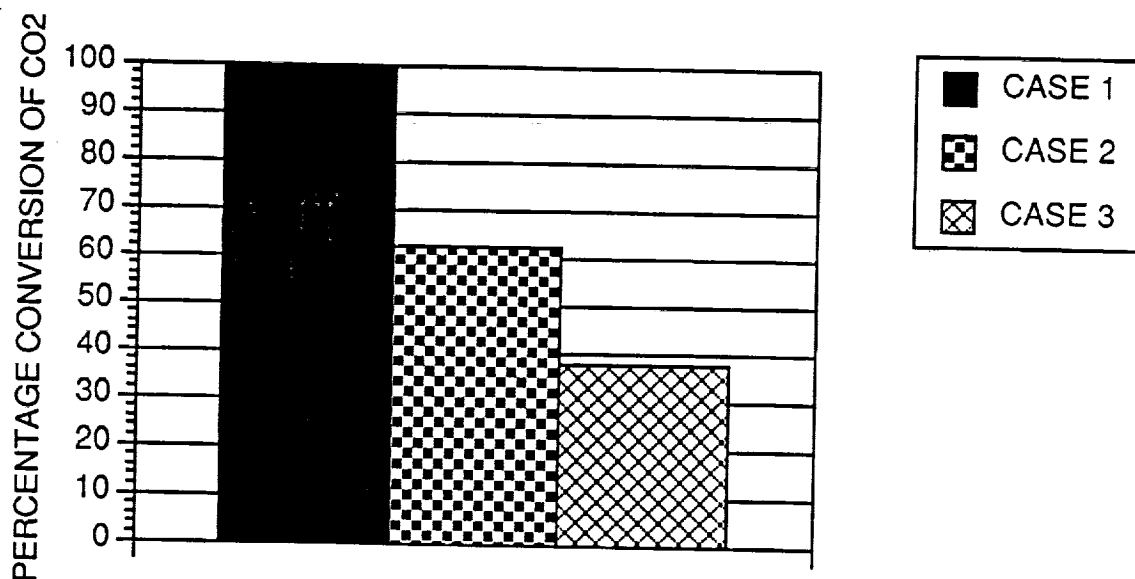


Figure 29A: Comparison of efficiency for different bleed fractions.

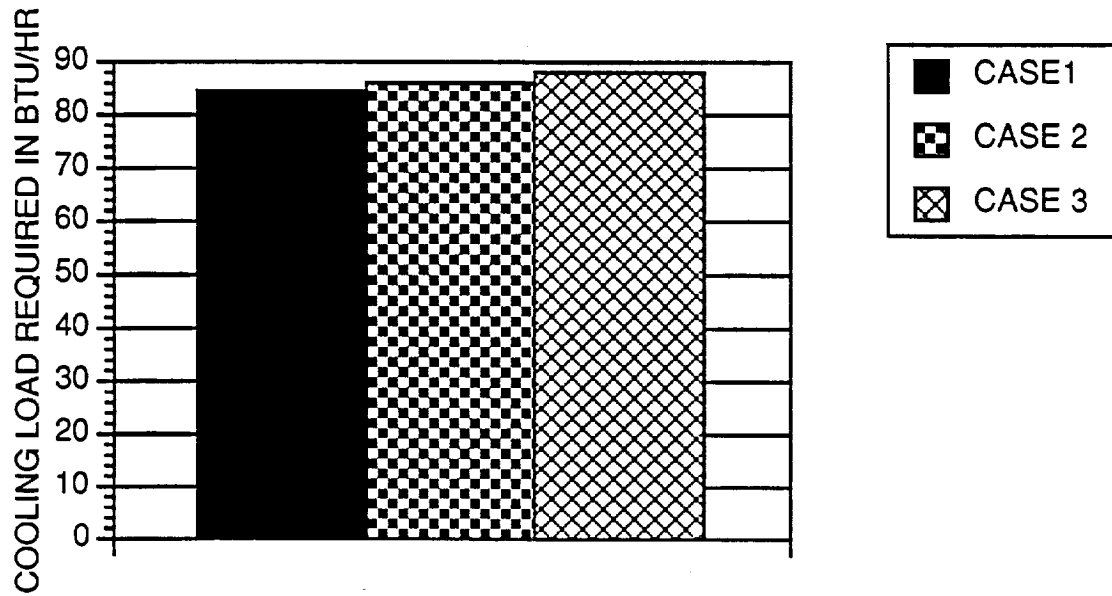


Figure 29B : Comparison of cooling loads for different bleed fractions

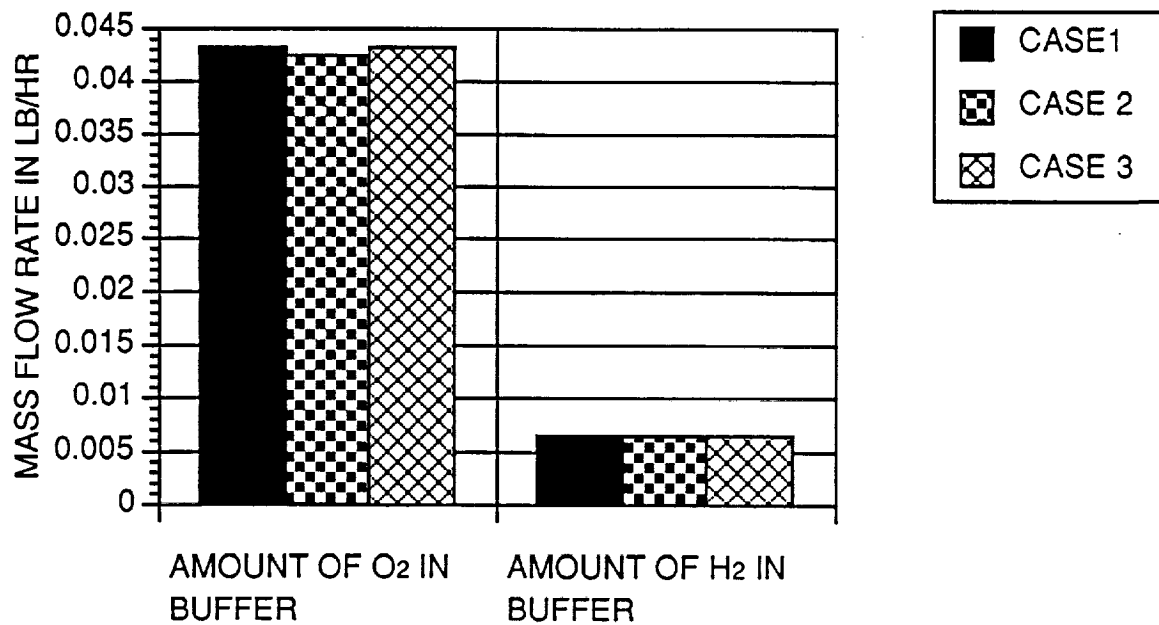


Figure 29C : Overall effect on the system for the different bleed fractions adopted

The result shown in Figure 29A is in accordance with the values reported in literature (Spina and Lee,1985). The single pass efficiency for a Bosch reactor using iron catalysts is reported to be less than 10%. The value calculated from our model (bleed fraction equal to 1.0) is 37.6%. This discrepancy could be explained by the over estimation in our model where Gibbs equilibrium is assumed to be attained in both the reactors. This does not occur under actual operating conditions, as mentioned earlier in chapter 4. With the total recycle, (bleed fraction equal to 0.0) conversion of 99.6% is attained which is again in accordance with Lee's results, (Spina and Lee,1985).

The integrated ECLSS model can also be used to study the effect of varying the cabin conditions on the overall system. The result of our analysis can be used to determine an optimum between cabin conditions and amount of expendables to be supplied or stored. Two sample cases are observed for different environment specifications in the cabin. Both the cases are for one man operating at basal metabolic rate. The situations are as:

Table 4: Different scenarios for cabin environment

Mole fraction of gases in the cabin	Case 1	Case 2
Oxygen	0.208	0.160
Nitrogen	0.769	0.769
Water vapor	0.02	0.068
Carbon dioxide	0.003	0.003

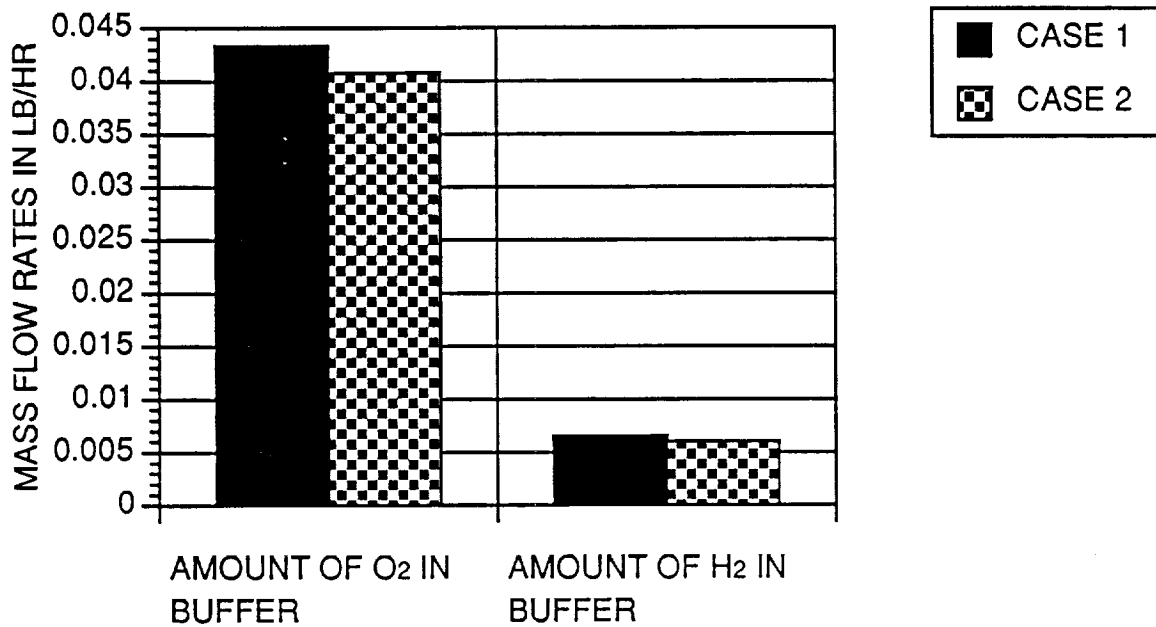


Figure 30: Comparison of the effect on the overall LSS for different cabin environments.

As shown in Figure 30 Case 1 is optimum compared to Case 2 as more O₂ and H₂ is stored in the buffer. This shows that the optimum cabin requirement is Case 1 which is same as the standard requirements for the cabin,(Humphries et al, 1986)

6 THERMODYNAMIC ANALYSIS OF THE CLOSED LOOP LIFE SUPPORT SYSTEM

The goal of any energy conservation study is to establish the minimum amount of energy necessary to operate a certain process. In the study which was carried out, (Brandhorst, 1991) the per capita power consumption for a partially closed and completely closed regenerable life support system were estimated as 3.5 kw/individual and 10 - 12 kw/individual respectively.

The objective of this chapter is to present an estimate of an alternative energy efficiency of the various sub units comprising the closed loop life support system calculated on the basis of the second law of thermodynamics.

Why second law?

In designing different LSS modules scientists usually consider the efficiency of the equipment based on the first law of thermodynamics. It has been shown in general that the average first law efficiency of most process is about 50%, (Cook, 1971).

However in a long term application we may be faced with the problem of **entropy crisis**. A system is using energy sources of low entropy probably solar and releasing energy of higher entropy. This is of concern to us because our goal should be to keep the net entropy production of a system as low as possible, and still ensure a positive entropy gradient between the system and the surroundings. As the net entropy production of a system increases, the entropy gradient between the system and the surrounding decreases and the system will gradually approach equilibrium with the surroundings until reaching the point where the entropy gradient is equal to zero. At this point no work can be extracted from the system. A measure of this

entropy generation can be obtained by evaluating the second law efficiency of the process.

From another perspective, from literature, the second law efficiency of a process is usually about 10%, (Reistad,1980). This indicates that 90% of the available work is usually lost in irreversibilities. Thus, the second law efficiency indicates that there is a great margin for improvement in the design of equipments auguring well for further large and rapid increases in efficiency.

Methodologies available for the second law analysis

The lowest energy we use can be derived from the application of the second law of thermodynamics. Quantities such as the available energy may be used to describe the irreversibilities of the process, (Denbigh, 1957). There are two widely used methods to study the process irreversibilities. They are :

- **Availability analysis /Exergy analysis.**
- **Lost work analysis.**

We shall now dwell briefly upon the steps followed for each of the above methodologies.

Availability Analysis

The technique of Availability Analysis was first proposed by Guoy and Stodola (Guoy, 1889 and Stodola 1898). Over the past years Availability Analysis has been extensively used in ares ranging from space heating to cryogenic processes, (Herbert and Stephen 1980, Ahern ,1980 (a)).

Many processes occur in an atmosphere which for all practical purposes is an inexhaustible source (or sink). The process is usually occurring because the system is not in thermal, mechanical or chemical equilibrium with the surroundings. The tendency of any natural process is to come to equilibrium with the surroundings.

This equilibrium state is known as the "dead state", (Moran, 1982). In the dead state there is no spontaneous change occurring within the system or the environment, or no spontaneous interaction between the two.

As the system moves towards its dead state it expends energy. Maximum work can be extracted if the system under study undergoes a totally reversible process in coming to its dead state. This maximum work is called as "available work". For an open system where there is inflow and outflow of mass, the available energy associated with mass inflow is termed as "exergy", (Moran, 1982).

The following general equation has been proposed to calculate the exergy at a point in the system (Ahern, 1980)

$$\begin{aligned} \text{Exergy} = (U - U_0) - T_0 (S - S_0) + \frac{P_0}{J}(v - v_0) + \frac{v^2}{2gJ} + (z - z_0)\frac{g}{gcJ} + \sum_c (\mu_c - \mu_0)W_c + E_i A_i F_i (3T^4 - T_0^4 - 4T_0 T_3) + \dots \end{aligned} \quad (32)$$

where :

$(U - U_0)$ is the internal energy

$T_0 (S - S_0)$ is the entropy

$\frac{P_0}{J}(v - v_0)$ is the work

$\frac{v^2}{2gJ}$ is the momentum

$(z - z_0)\frac{g}{gcJ}$ is work done against gravity

$\sum_c (\mu_c - \mu_0)W_c$ is the chemical work

$E_i A_i F_i (3T^4 - T_0^4 - 4T_0 T_3)$ is radiation emission

the subscript 0 indicates the reference state or the environment

The thermodynamic efficiency based on exergetic analysis may be defined as, (Chiu and Newton, 1980)

$$\text{Thermodynamic efficiency} = \frac{\text{exergy in product}}{\text{exergy supplied to the system}} \quad (33)$$

Lost Work Analysis

The method of lost work analysis was first proposed by Seader, (Nevers and Seader, 1980).

The basic requirement of the second law is :

The total entropy change of an isolated system,

$$\Delta S_{\text{sys}} \geq 0.0 \quad (34)$$

For a control volume with a steady state process where the surroundings are at a temperature of T_0 , the total entropy change of the system is given by, (Smith and Van Ness 1987)

The rate of change of total entropy of the system = Net rate of entropy transfer by flowing streams + Rate of entropy exchange with the surroundings

Thus

$$\Delta(Sm)_{fs} - \frac{Q}{T_0} > 0.0 \quad (35)$$

where $\Delta(Sm)_{fs}$ is the difference in entropy between the feed and the product

Q is the net heat transfer from the system to the surroundings

For a steady state flow process there is no internal energy accumulation within the system. The law of conservation of energy can be expressed as ,

$$\Delta \left[\left(H + \frac{1}{2} u^2 + zg \right) \right]_{fs} = Q - W_s \quad (36)$$

where $\Delta \left[\left(H + \frac{1}{2} u^2 + zg \right) \right]_{fs}$ is the difference in energy between the in flow and the outflow streams.

Q is the heat flow into the system

W_s is the work done by the system

For any system which requires work the amount of work required will be a minimum if the system undergoes a reversible change. This minimum work required is called the "ideal work", (W_{ideal}). Since there is no degradation of work the entropy generation for a reversible process is equal to zero and equation (35) becomes

$$Q = T_0 \Delta(Sm)_{fs}$$

Substituting the above value in equation (36) and rearranging gives

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - \Delta \left[\left(H + \frac{1}{2} u^2 + zg \right) \right]_{fs} \quad (37)$$

In most processes the kinetic and potential energy terms are negligible, and equation (37) can be written as

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - (\Delta H)_{fs} \quad (38)$$

It is justified to mention here that from an availability viewpoint, according to the definition of W_{ideal} as given in (38), the minimum work required is equivalent to the difference in availability between the input and the output streams.

For a work producing process the "lost work" is the work which is lost due to irreversibilities within the process. It is expressed as the difference between the ideal work which could be produced by the process (W_{ideal}) and the actual work

produced by the process (W_s). Thus from equations (36) and (38), W_{lost} can be written as

$$W_{lost} = T_0 \Delta(S_m)_{fs} - Q \quad (39)$$

Conventionally, there are two kinds of processes. A spontaneous process is one which produces work, i.e. W_{ideal} is positive. Then

$$W_s = W_{ideal} - W_{lost} \quad (40)$$

A nonspontaneous process is one which requires some form of external work to be supplied, i.e. W_{ideal} is negative. Hence

$$|W_s| = |W_{ideal}| + W_{lost} \quad (41)$$

Thereby the second law efficiency for each type of process can be defined as

$$\eta_2 (\text{spontaneous process}) = \frac{W_s}{W_{ideal}} \quad (42)$$

$$\eta_2 (\text{nonspontaneous process}) = \frac{W_{ideal}}{W_s} \quad (43)$$

For our analysis we used the Lost Work analysis method. The reasons for doing so are enumerated below

- Calculation of lost work gives us a more intuitive insight into the energy loss within the process.
- For a process where the goal is to produce a stream having high availability, the calculation of a availability loss in the output stream makes no sense. However in the lost work approach we are only concerned with the irreversibilities within the process.

Method of Approach

The technique adopted to calculate the thermodynamic efficiency of the ECLSS is:

- (1) The process boundary is defined.

(2) Consistent heat and material balance data is obtained. This data is obtained from our ASPEN model of the ECLSS.

(3) Selection of ambient temperature as a reference. We choose the cabin temperature of 70° F.

(4) Evaluating the W_{lost} within each functional unit of the ECLSS subsystem.

(5) Calculating the W_{ideal} for each subsystem based on the subsystem information.

(6) Knowing the W_{lost} and W_{ideal} the second law efficiency of each subsystem is evaluated.

Results

The advantage of the lost work analysis was demonstrated by applying this technique to a few ECLSS sample technologies. The stream information like enthalpy, entropy, and mass flow rates were obtained from our integrated ASPEN model. The values are obtained for a basal case of a crew of 1 man of 25 years of age weighing 60 kg operating at basal metabolic rate.

Wet Oxidation of Solid Waste

Refer Figure 24 for stream identification.

Table 5: Properties of streams involved in wet oxidation process.

St Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	3.44×10^{-4}	12.91×10^{-4}	23.56×10^{-7}
S2	9.16×10^{-4}	-1.4×10^{-3}	-2.64×10^{-3}
S3	1.26×10^{-3}	-4.77	-3.63×10^{-6}
S4	1.26×10^{-3}	-4.85	1.72×10^{-5}
S5	0.0	0.0	
Q1	Heat Duty =	-4.77 Btu/hr	
Q2	Heat Duty =	-0.08 Btu/hr	

The lost work analysis of each unit operation block comprising the solid waste oxidizer is given in Table 6.

Table 6: Lost work estimation of the solid waste oxidizer

Unit Operation block	Lost work (Btu/hr)	% of total lost work
Wet oxidizer	4.71	98.1
Depressurizer	0.091	1.9
Total lost work	4.801	

$$\text{Wideal} = 530 (1.72 \times 10^{-5} + 2.64 \times 10^{-3} - 23.56 \times 10^{-7}) - (-4.85 -$$

$$12.91 \times 10^{-4} + 14.05 \times 10^{-4})$$

$$= 6.26 \quad \text{Btu/hr}$$

Wideal being positive this is a spontaneous process. Hence

$$W_s = 6.26 - 4.801$$

$$= 1.459$$

$$\eta_2 = \frac{1.459}{6.26}$$

$$= 23.3\%$$

Catalytic Oxidation of Trace Contaminant Gases:

Refer Figure 15 for stream identification.

Table 7: Stream properties of Catalytic oxidation subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	35.66	-3291.38	1.17
S2	3.45	-318.44	0.113
S3	3.45	135.9	0.71
S4	3.45	309.64	0.86
S5	3.45	309.33	0.86
S6	3.45	-145.0	0.39
S7	32.21	-2972.98	1.05
S8	32.21	-2975.56	1.05
S9	35.66	-3120.25	1.49
Q1	Heat duty =	173.7	(Btu/hr)
Q2	Heat duty =	-0.297	(Btu/hr)
Q3	Heat duty =	-2.56	(Btu/hr)

The lost work analysis of each unit operation block comprising the Catalytic Oxidizer is shown in Table 8.

Table 8: Lost work estimation of Catalytic oxidation subsystem

Unit operation block	Lost work (Btu/hr)	% of total lost work
Diverter	0.0	0.0
Heat exchanger	67.31	38.2
Heater	79.5	45.1
HTCO	0.297	0.17
LTCO	2.56	1.45
Mixer	26.5	15.04
Total lost work	176.17	

$$\begin{aligned} W_{\text{ideal}} &= 530 (1.49 - 1.17) - (-3120.25 + 3291.38) \\ &= -1.53 \text{ Btu/hr} \end{aligned}$$

This is a non spontaneous process. Hence

$$\begin{aligned} W_s &= 1.53 + 176.17 \\ &= 177.7 \text{ Btu/hr} \\ \eta_2 &= \frac{1.53}{177.7} \\ &= 0.86\% \end{aligned}$$

Bosch subsystem

Refer Figure 19 for stream identification. The bleed stream fraction is assumed to be zero.

Table 9: Stream properties of Bosch subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	0.048	-183.79	-6.04×10^{-4}
S2	4.37×10^{-3}	-54.16×10^{-6}	-5.98×10^{-7}
S3	0 0.398	-677.1	-0.139
S4	0.398	515.04	0.778
S5(solid)	1.3×10^{-2}	4.51	4.27×10^{-3}
S5(vapor)	0.385	-130.4	0.436
S6	3.9×10^{-2}	-268.11	-0.087
S7(solid)	1.3×10^{-2}	-0.08	-1.5×10^{-4}
S7(vapor)	0.346	-507.11	-0.177
S8	1.3×10^{-2}	-0.015	-2.87×10^{-5}
S9	0.398	-677.1	-0.139
Q1	Heat duty =	1192.14	Btu/hr
Q2	Heat duty =	-640.93	Btu/hr
Q3	Heat duty =	-649.41	Btu/hr

Table 10 indicates the amount of lost work in each functional unit comprising the Bosch subsystem.

Table 10: Lost work analysis of unit operation blocks of Bosch subsystem

Unit operation block	Lost work (Btu/hr)	% lost work
Mixer	6.89	0.55
Reactor 1	486.01	39.04
Reactor 2	461.95	37.11
Condensate remover	276.13	22.18
Solid carbon remover	13.78	1.11
Total lost work	1244.76	

$$\begin{aligned}
 -W_{\text{ideal}} &= 530 \left(-2.87 \times 10^{-5} - 0.087 + 6.21 \times 10^{-4} + 5.98 \times 10^{-7} - 1.72 \times 10^{-5} \right) - \\
 &\quad \left(-286.11 - 0.015 + 178.94 + 54.16 \times 10^{-6} + 4.85 \right) \\
 &= 38.53 \quad \text{Btu/hr}
 \end{aligned}$$

Hence this is a spontaneous process.

$$\begin{aligned}
 W_s &= 38.53 - 1244.76 \\
 &= -1206.23
 \end{aligned}$$

This is an example of a highly non ideal process. The actual process is spontaneous however under simulated working conditions the process requires external work to be supplied.

Static Feed Water Electrolysis

Refer Figure 23 for stream identification.

Table 11: Properties of streams present in the Water Electrolysis Subsystem.

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	9.6×10^{-2}	-654.8	-0.21
S2	9.6×10^{-2}	-654.83	-0.21
S3	9.6×10^{-2}	-654.83	-0.21
S4	9.6×10^{-2}	-0.38	-0.27
S5	1.07×10^{-2}	-0.25	-4.76×10^{-4}
S6	8.52×10^{-2}	-0.13	-2.46×10^{-4}
Q1	Heat duty =	-0.03 Btu/hr	
Q2	Heat duty =	654.55 Btu/hr	

Table 12: Lost work analysis within the Water Electrolysis Subsystem

Unit operation block	Lost work (Btu/hr)	% lost work
Pump	0.427	0.38
Cooler	0.03	0.03
Electrolyzer	96.99	87.08
Gas separator	13.93	12.51
Total lost work	111.38	

$$\begin{aligned}
 W_{\text{ideal}} &= 530 (-4.76 \times 10^{-4} - 2.46 \times 10^{-4} + 0.21) - (-0.13 - 0.25 + 654.8) \\
 &= -543.5 \text{ Btu/hr}
 \end{aligned}$$

W_{ideal} being negative, this is a spontaneous process.

$$\begin{aligned}
 W_s &= -654.88 \text{ Btu/hr} \\
 \eta_2 &= \frac{543.5}{654.88} \\
 &= 82.99\%
 \end{aligned}$$

Humidity Condensate Removal

Refer Figure 16 for stream identification.

Table 13: Stream properties of streams occurring in Humidity Condensate Remover

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	35.66	-3120.22	1.49
S2	7.18×10^{-2}	-489.58	-0.154
S3	35.59	-2783.35	1.35
Q1	Heat duty =	-152.71	Btu/hr

Since the heat of condensation is not being used to do any useful work, hence,

$$\begin{aligned}
 \text{Lost work} &= 530 (1.35 + 0.154 - 1.49) + 152.71 \\
 &= 160.13 \text{ Btu/hr}
 \end{aligned}$$

$$\begin{aligned}
 W_{\text{ideal}} &= 530 (1.35 + 0.154 - 1.49) - (-489.58 - 2783.35 + 3120.22) \\
 &= 160.13 \text{ Btu/hr}
 \end{aligned}$$

$$W_s = 0$$

$$\text{Thus } \eta_2 = 0$$

This is valid since we had assumed that the heat of condensation is not used for doing useful work, thereby the amount of work which can be obtained from the process is zero.

7 CONCLUSIONS AND RECOMMENDATIONS

We arrive at the following conclusions from the first part of this project :

The integrated Environmental Control and Life Support System (EELS) model can be used to assess the parameter requirements for different space station conditions. The utility of a particular configuration is judged on the basis of the amount of oxygen and hydrogen stored in their respective buffers and the heating/cooling load required. The excess oxygen and hydrogen is stored as a reserve for cases of exigency for example to provide oxygen to the cabin if there occurs a failure in the oxygen generation unit. However the oxygen and hydrogen stored in the buffer will bear an impact on the load carrying capability of the space shuttle. This has not been explored in our present model.

Recommended future work in this area is :

- To develop a more rigorous model of the various EELS components like the water electrolysis system and the CO₂ membrane removal system.
- To develop a rigorous dynamic biological model of the crew.
- To develop a dynamic model of the entire ECLSS using the values obtained from our steady state model as the initial values.

The latter part of this project was concerned with the 'lost work' analysis. An analysis of lost work at the subsystem component level enables the designer to identify principal sources of entropy generation and strive to minimize them. Thus the overall conclusion to be drawn from this work is that there exists a potential for energy conservation in the currently used ECLSS technologies which warrants evaluation of the present operating conditions. In order to arrive at a detailed

optimum design of the ECLSS subsystem it is recommended to evaluate the lost work for every hardware component constituting the subsystem which would enable the designer to exactly pin point the areas of maximum entropy generation.

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APPENDIX 1

DETAILED DERIVATION OF EQUATIONS USED FOR THE COMPARTMENT
MODEL OF THE HUMAN RESPIRATORY TRACT

Upper Respiratory Tract

Ideal gas law holds good . Therefore:

$$Q_1 / (70 + 460) = Q_2 / (98.6 + 460) \quad (A1)$$

Lower Respiratory Tract

$$\begin{aligned} \text{Volume of water entering the compartment} &= 15 / (760 - 15) \\ &= 0.021 \quad \text{lit/lit of dry gas} \end{aligned}$$

$$\begin{aligned} \text{Volume of water leaving the compartment} &= 47 / (760 - 47) \\ &= 0.066 \quad \text{lit/lit of dry gas} \end{aligned}$$

$$\begin{aligned} \text{Volume of dry gas entering} &= Q_2 - 0.021 \times Q_2 \\ &= 0.98 \times Q_2 \quad \text{lit} \end{aligned}$$

$$\begin{aligned} \text{Total volume of water present in outgoing gas} &= 0.066 \times 0.98 \times Q_2 \\ &= 0.065 \times Q_2 \quad \text{lit} \end{aligned}$$

Thereby total volume of gas leaving the compartment (Q3) is given by :

$$Q_3 = (0.065 + 0.98) \times Q_2 \quad (A2)$$

Since no exchange of N₂, CO₂ or O₂ occurs in the lower respiratory tract.

Therefore the outgoing mole fractions of O₂, CO₂ and N₂ will be given by

$$Y_x^i \times Q_2 = Y_x^o \times Q_3 \quad (A3)$$

where Y_x^i mole fraction of species x (may be O₂, CO₂ or N₂) in Q₂
 Y_x^o mole fraction of species x in Q₃

Lungs:

Solving equations (21) to (24) as given in chapter 3

$$Q_4 = (Q_3 \times (Y_{O_2^i} + Y_{CO_2^i} + Y_{N_2^i}) - VO_2 + VCO_2) / 0.938 \quad (A4)$$

The concentration of the outgoing gas from the lungs is calculated using the following equations :

$$Y_{O_2} = ((Q_3 \times Y_{O_2^i}) - VO_2) / Q_4 \quad (A5)$$

$$Y_{CO_2} = ((Q_3 \times Y_{CO_2^i}) + VCO_2) / Q_4 \quad (A6)$$

$$Y_{N_2} = (Q_3 \times Y_{N_2^i}) / Q_4 \quad (A7)$$

$Q_1, Q_2, Q_3, Q_4, VO_2, VCO_2, V_E, Y_{O_2}, Y_{N_2}$ and Y_{CO_2} are as defined in chapter 3.

MO_2 the volume of O_2 required for metabolism is related to VO_2 by,

$$MO_2 = (VO_2 / 60.0) \times (273 / 310) \quad (A8)$$

and $Q_3 = V_E \times 60.0 \quad (A9)$

The total mass flow rates in lb/hr of component i (where i can be O_2, N_2, CO_2 or H_2O) in expired air (M_i^{exp}) and in inspired air (M_i^{ins}) is given by :

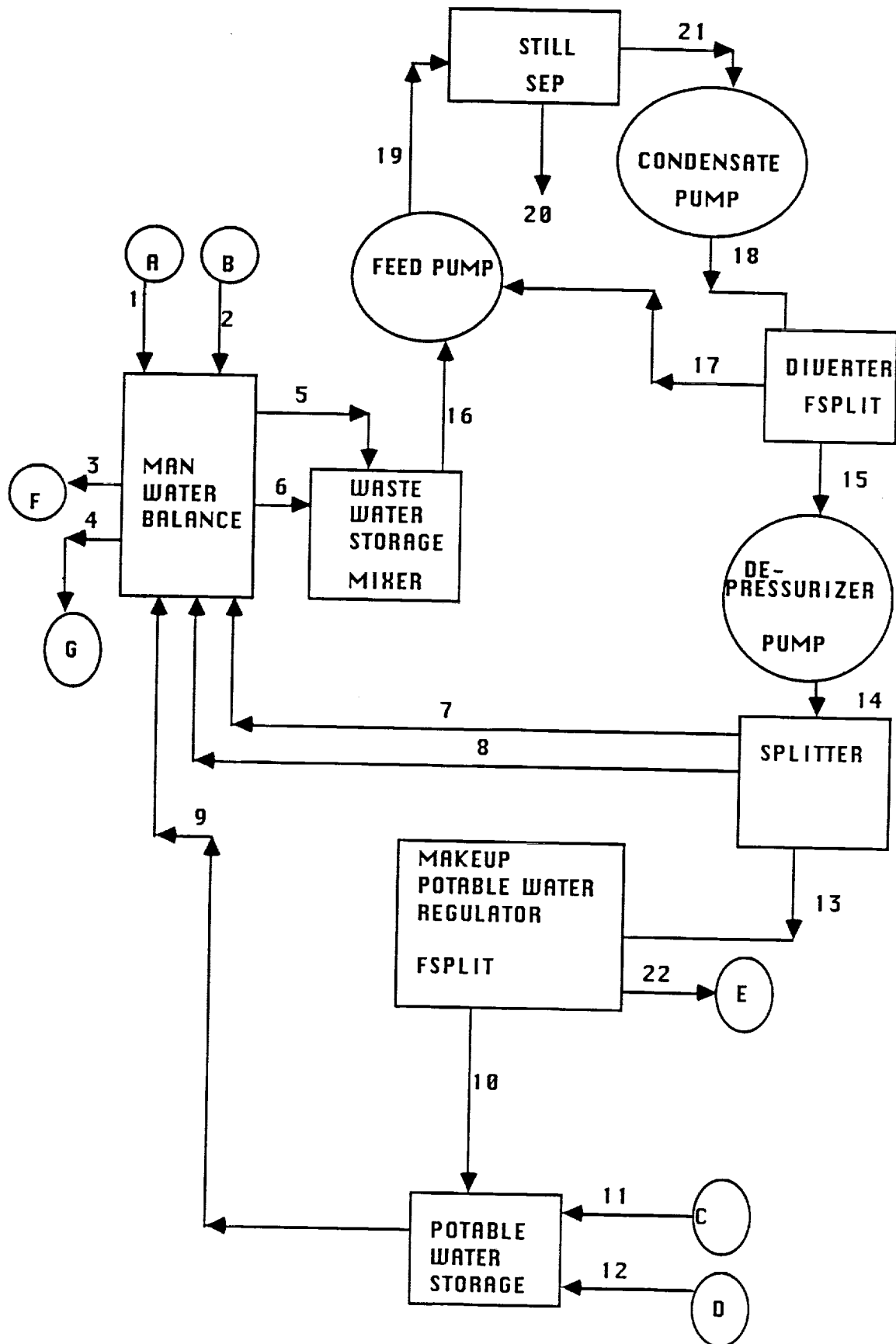
$$M_i^{exp} = (Q_4 \times Y_i \times \text{molecular weight of } i \times 0.035) / (0.7302 \times 558.6) \quad (A10)$$

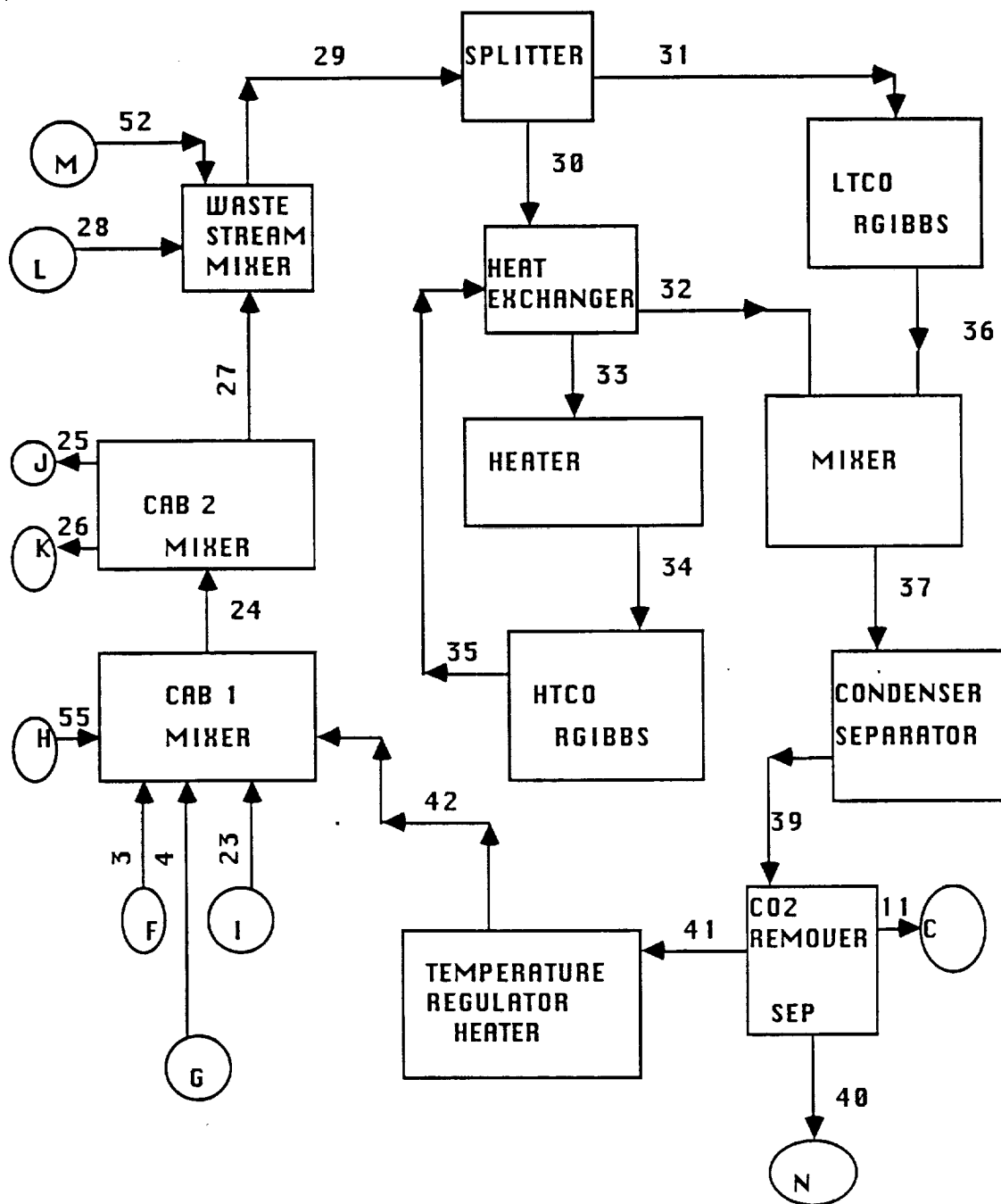
$$M_i^{ins} = (Q_4 \times Y_i^i \times \text{molecular weight of } i \times 0.035) / (0.7302 \times 530.0) \quad (A11)$$

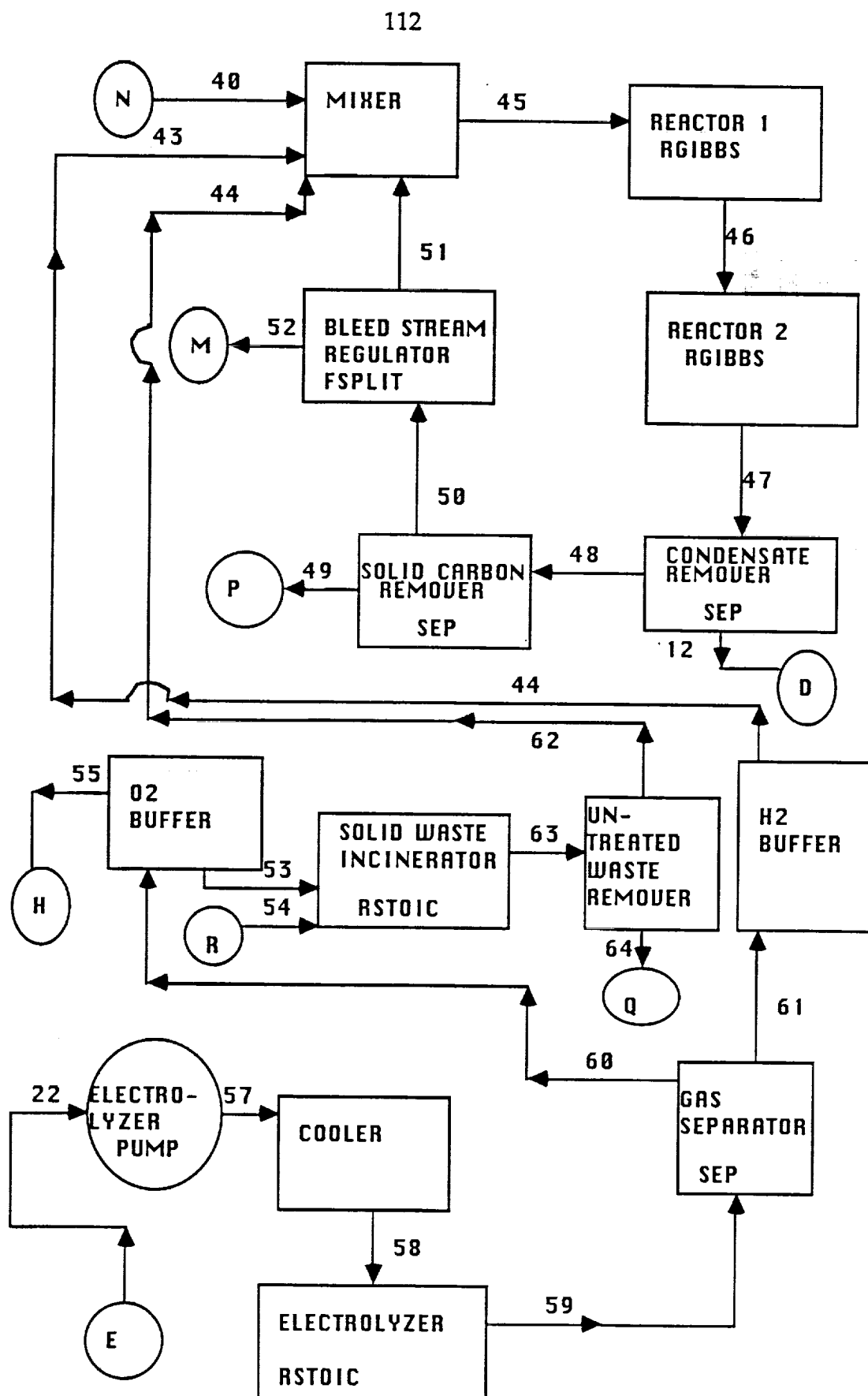
APPENDIX 2

BLOCK FLOW DIAGRAM OF THE INTEGRATED ECLSS MODEL WITH THE CREW

The integrated ASPEN model of the ECLSS is included here. Man is shown as a regular block.

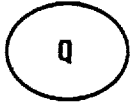
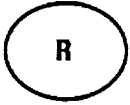






NOMENCLATURE :

A	WATER PRESENT IN FOOD
B	WATER GENERATED DUE TO METABOLISM OF FOOD
C	HUMIDITY CONDENSATE
D	CONDENSATE WATER FROM CO₂ REDUCTION
E	WATER USED FOR OXYGEN GENERATION
F	SWEAT GENERATED BY THE CREW
G	EXCESS WATER USED FOR SATURATING THE EXPIRED AIR
H	MAKEUP OXYGEN FROM THE BUFFER TO THE CABIN
I	EXPIRED AIR FROM THE CREW
J	AIR LEAK FROM THE CABIN
K	AIR INSPIRED BY THE CREW
L	TRACE CONTAMINANT STREAM
M	BLEED STREAM FROM THE CARBON DIOXIDE REDUCTION PROCESS
P	SOLID CARBON GENERATED IN THE BOSCH REACTOR

NOMENCLATURE CONTINUED :**UNTREATED SOLID WASTE****SOLID WASTE FROM CREW TO BE TREATED**

APPENDIX 3

THIS IS AN ASPEN SOLUTION CONSIDERING THE MAN IN THE CABIN
; APPENDING EACH ECLSS MODULE TO THE CABIN BLOCK

```
; SPECIFYING THE UNIT SYSTEM FOR INPUT INFORMATION
IN-UNITS ENG
; SPECIFYING THE UNIT SYSTEM FOR OUTPUT INFORMATION
OUT-UNITS ENG
; DEFINE COMPONENTS THAT ARE IN THE SYSTEM
COMPONENTS C1 WATER/CO2 CO2 /C3 HYDROGEN/C4 NITROGEN/C5 OXYGEN/C6 CH4
COMPONENTS C7 CARBON-MONOXIDE/C9 ACETYLENE/C12 C
COMPONENTS C13 ETHYLENE/C14 ETHANE/C2 UREA
DATABANKS SOLIDS/DIPPRPCD
; SPECIFYING PHYSICAL PROPERTY OPTIONS
PROPERTIES SYSOP0
```

```
; FLOWSHEET SECTION OF ASPEN INPUT FILE
; THIS SECTION IS FOR WATER REGENERATION SUBSYSTEM
```

FLOWSHEET WATERREGENERATION

BLOCK HEAT11	IN=METW PW01 FOODW	OUT=HE11OUT
BLOCK WASEP	IN=HE11OUT	OUT=WAEX1
BLOCK W1	IN=URINE	OUT=URINE1
BLOCK MIX12	IN=URINE1 S11 FD1U	OUT=FD1OUT
BLOCK MIX18	IN=S2 MAKEUPS2	OUT=S21
BLOCK MIX15	IN=S21 SS2	OUT=FD2OUT
BLOCK MIX13	IN=FD1OUT FD2OUT	OUT=F1
BLOCK SPTT2	IN=CON1	OUT=CON2 CONR
BLOCK STILL	IN=FOUT	OUT=CON BRINE
BLOCK P1	IN=F1 CONR	OUT=FOUT
BLOCK P4	IN=CON	OUT=CON1
BLOCK P5	IN=CON2	OUT=CON3
BLOCK SPTT3	IN=CON3	OUT=S1 S2 S3
BLOCK SPTT4	IN=S3	OUT=S3OUT MAKEUPPOT
BLOCK MIX20	IN=S1 URFLUSH	OUT=S11
BLOCK W2	IN=WA	OUT=WA1
BLOCK POTMIX	IN=MAKEUPPOT DECAN WA1	OUT=PWO
BLOCK POTSEP	IN=PWO	OUT=PWO1 PWOEX

```
; THIS SECTION IS FOR TRACE REMOVAL, DEHUMIDIFICATION, CO2
; REMOVAL, AND PART OF CO2 REDUCTION
```

FLOWSHEET INITIAL

BLOCK CAB1	IN=N2O2 CABCO2 CABH2O EXHAIR SW	OUT=CAB1OUT
BLOCK CAB2	IN=CAB1OUT	OUT=AIRLEAK INSAIR AIROUT
BLOCK MIX2	IN=AIROUT TC BLEED1 EX	OUT=OUTM
BLOCK SPLT1	IN=OUTM	OUT=LT HT
BLOCK HEE1	IN=HT HEIN	OUT=HEOUT2 HEATOUT
BLOCK HEA6	IN=HEATOUT	OUT=HEA6OUT
BLOCK GIBB1	IN=HEA6OUT	OUT=HEIN
BLOCK GIBB2	IN=LT	OUT=GIBBOUT
BLOCK MIXT	IN=GIBBOUT HEOUT2	OUT=HUHXOUT
BLOCK HEA2	IN=HUHXOUT	OUT=CAIR WA
BLOCK SEP3	IN=CAIR	OUT=ABAIR1 SEPC EX

```

BLOCK COOL    IN=ABAIR1                OUT=ABAIR
BLOCK MIX5    IN=SEPC SEPOUT2  HYDRO WASCO21  OUT=MIX5OUT
BLOCK REAC1   IN=MIX5OUT                OUT=REA1

; THIS SECTION IS FOR REMAINING CO2 REDUCTION SUBSYSTEM
; INVOLVING SOLID CARBON AND FOR THE SOLID WASTE INCINERATOR
; SUBSYSTEM
FLOWSHEET MIDDLE
BLOCK CHNGR1  IN=REA1                  OUT=REA1OUT
BLOCK REAC2   IN=REA1OUT               OUT=REA2
BLOCK HE1     IN= REA2                 OUT= HE1OUT DECAN
BLOCK SEPA    IN=HE1OUT               OUT=SEPOUT SOLIDC
BLOCK SEPA1   IN=SEPOUT               OUT=SEPOUT1 BLEED
BLOCK SOLIDINC IN=SOLIDW WASO2        OUT=WASCO2A
BLOCK SOLP    IN=WASCO2A              OUT= WASCO2 WASC

; THIS SECTION INCLUDES THE O2 GENERATION SUBSYSTEM
FLOWSHEET FINAL
BLOCK CHNGR3  IN=SEPOUT1              OUT=SEPOUT2
BLOCK PSFE    IN=REM WATER S31 PWOEX1  OUT=PSFEO
BLOCK HSFE    IN=PSFEO                OUT=HSFEO
BLOCK STOIC1  IN=HSFEO                OUT=STOIC1OUT
BLOCK SEPSFE  IN=STOIC1OUT            OUT=HYD1 OXYG1 REMWATER
BLOCK CHNGR7  IN=S3OUT                OUT=S31
BLOCK CHNGR8  IN=WASCO2               OUT=WASCO21
BLOCK CHNGR9  IN=BLEED                OUT=BLEED1
BLOCK CHNGR10 IN=PWOEX1               OUT=PWOEX1

; SPECIFY FEED STREAMS

DEF-STREAMS MIXCISLD MIDDLE WATERREGENERATION

STREAM EXHAIR PRES=1[ATM] TEMP=98.6 NPHASE=1
MASS-FLOW C1 0.5/CO2 0.5/C4 3.0/C5 2.0
STREAM TC PRES=1[ATM] TEMP=70.0 MASS-FLOW=3.27D-4
MASS-FRAC C7 0.84/C6 0.084/C14 0.00056/C13 0.000014/C9 0.00014/ &
C3 0.075
STREAM HYDRO PRES=1[ATM] TEMP=70.0
MASS-FLOW C3 100.0
STREAM FD1U
SUBSTREAM CISOLID TEMP=98.6 PRES=1[ATM]
MASS-FLOW C2 0.001
STREAM SS2
SUBSTREAM CISOLID TEMP=70 PRES=1[ATM]
MASS-FLOW C2 1D-5
STREAM METW TEMP=98.6 PRES=1[ATM]
MASS-FLOW C1 0.01
STREAM MAKEUPS2 PRES=1[ATM] TEMP=70.0
MASS-FLOW C1 10.0
STREAM URFLUSH TEMP=70.0 PRES=1[ATM]
MASS-FLOW C1 100.0
STREAM CABCO2 TEMP=69.0 PRES=1[ATM] NPHASE=1 PHASE=V
MASS-FLOW CO2 100.0
STREAM CABH2O TEMP=69.0 PRES=1[ATM] NPHASE=1 PHASE=V
MASS-FLOW C1 100.0

```

```

STREAM N2O2 TEMP=69.0 PRES=1[ATM] NPHASE=1 PHASE=V
  MASS-FLOW C4 100.0/C5 100.0
STREAM SOLIDW
  SUBSTREAM CISOLID PRES=1[ATM] TEMP=98.6
  MASS-FLOW C12 100.0
STREAM WASO2 TEMP=70 PRES=1[ATM]
  MASS-FLOW C5 100.0
STREAM FOODW TEMP=70 PRES=1[ATM]
  MASS-FLOW C1 100.0
STREAM SW TEMP=98.6 PRES=1[ATM] NPHASE=1 PHASE=V
  MASS-FLOW C1 100.0

```

```

; DESCRIPTION OF ALL THE BLOCKS INCLUDED IN THE PROGRAM

```

```

; BLOCKS FOR VCD AND MAN WATER BALANCE

```

```

BLOCK HEAT11 HEATER
  PARAM TEMP=98.6 PRES=1[ATM]
BLOCK WASEP FSPLIT
  PARAM PRES=1[ATM]
  MASS-FLOW WAEXH 0.5/ SW1 0.6
BLOCK MIX12 MIXER
BLOCK MIX15 MIXER
BLOCK MIX13 MIXER
  PARAM PRES=20.0
BLOCK SPTT2 FSPLIT
  FRAC CONR 0.6
BLOCK STILL SEP
  FRAC STREAM=BRINE SUBSTREAM=MIXED COMPS=C1 FRACS=0.8
  FRAC STREAM=BRINE SUBSTREAM=CISOLID COMPS=C2 FRACS=1.0
  FLASH-SPECS CON TEMP=70 PRES=0.5 NPHASE=1 PHASE=L
  FLASH-SPECS BRINE TEMP=70 PRES=0.5 NPHASE=1 PHASE=L
BLOCK P1 PUMP
  PARAM PRES=0.5 NPHASE=2 MAXIT=60 TOL=0.01
BLOCK P4 PUMP
  PARAM PRES=20.0 NPHASE=2 MAXIT=60 TOL=0.01
BLOCK P5 PUMP
  PARAM PRES=14.7 NPHASE=2 MAXIT=60 TOL=0.01
BLOCK SPTT3 FSPLIT
  MASS-FLOW S1 0.01/S2 2.3
BLOCK SPTT4 FSPLIT
  PARAM PRES=1[ATM] NPHASE=1 PHASE=L
  FRAC MAKEUPPOT 0.5
BLOCK POTMIX MIXER
BLOCK POTSEP FSPLIT
  PARAM PRES=1[ATM]
  MASS-FLOW PW01 0.1
BLOCK MIX18 MIXER
BLOCK MIX20 MIXER
BLOCK CHNGR7 CLCHNG
BLOCK CHNGR10 CLCHNG

```

```

; BLOCKS FOR CABIN

```

```

BLOCK CAB1 MIXER
BLOCK CAB2 FSPLIT
  PARAM PRES=1[ATM] NPHASE=1

```

MASS-FLOW AIRLEAK 6.5D-3
R-FRAC AIROUT 0.98

; BLOCKS FOR TRACE REMOVAL SUBSYSTEM

BLOCK MIX2 MIXER
PARAM PRES=1[ATM]
BLOCK SPLT1 FSPLIT
PARAM PRES=1[ATM]
FRAC LT 0.7
BLOCK HEEX1 HEATX
PARAM T-COLD=600
FEEDS HOT=HEIN COLD=HT
PRODUCTS HOT=HEOUT2 COLD=HEATOUT
BLOCK HEA6 HEATER
PARAM TEMP=795.0
BLOCK GIBB1 RGIBBS
PARAM TEMP=795 PRES=1[ATM]
PROD C1/CO2/C4/C5/C3/C7/C6
BLOCK GIBB2 RGIBBS
PARAM TEMP=70 PRES=1[ATM] MAXIT=100 TOL=1D-2
PROD CO2/C1/C4/C5/C7/C6/C3
BLOCK MIXT MIXER
PARAM PRES=1[ATM]

; BLOCKS FOR DEHUMIDIFICATION

BLOCK HEA2 SEP
PARAM PRES=1[ATM]
FRAC STREAM=CAIR COMPS=C1 CO2 C4 C5 C6 C7 C3 FRACS=0.8 1.0 1.0 &
1.0 1.0 1.0 1.0
FLASH-SPECS WA TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=L
FLASH-SPECS CAIR TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=V
BLOCK COOL HEATER
PARAM TEMP=69.0 PRES=1[ATM]

; BLOCK FOR CO2 REMOVAL

BLOCK SEP3 SEP
FRAC STREAM=ABAIR1 COMPS=CO2 C1 C4 C5 FRACS=0.5 1.0 1.0 1.0
FRAC STREAM=EX COMPS=C6 C7 C3 CO2 FRACS=1.0 1.0 1.0 0.0
FLASH-SPECS ABAIR1 TEMP=70.0 PRES=1[ATM]
FLASH-SPECS SEPC TEMP=70.0 PRES=1[ATM]
FLASH-SPECS EX TEMP=70.0 PRES=1[ATM]

; BLOCKS FOR CO2 REDUCTION USING BOSCH

BLOCK MIX5 MIXER
PARAM PRES=1[ATM]
BLOCK REAC1 RGIBBS
PARAM TEMP=1300[K] PRES=1[ATM]
PROD CO2/C3/C7/C1/C6
BLOCK CHNGR1 CLCHNG
BLOCK REAC2 RGIBBS
PARAM TEMP=900[K] PRES=1[ATM]
PROD CO2/C3/C7/C6/C1/C12 S
BLOCK HE1 SEP
FRAC STREAM=HE1OUT SUBSTREAM=MIXED COMPS=C1 CO2 C3 C7 C6 &
FRACS=0.0 1.0 1.0 1.0 1.0

```

    FRAC STREAM=HE1OUT SUBSTREAM=CISOLID COMPS=C12 FRACS=1.0
    FLASH-SPECS DECAN TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=L
    FLASH-SPECS HE1OUT TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=V
BLOCK SEPA SEP
    FRAC STREAM=SEPOUT COMPS=CO2 C3 C7 C6 FRACS=1.0 1.0 1.0 1.0
    FLASH-SPECS SOLIDC TEMP=70 PRES=1[ATM] NPHASE=1 PHASE=S
    FLASH-SPECS SEPOUT TEMP=70 PRES=1[ATM] NPHASE=1 PHASE=V 1.0
BLOCK SEPA1 FSPLIT
    PARAM PRES=1[ATM]
    FRAC BLEED 0.0

```

```

BLOCK CHNGR3 CLCHNG

```

```

; BLOCKS FOR O2 GENERATION BY WATER ELECTROLYSIS

```

```

BLOCK PSFE PUMP
    PARAM PRES=30.0
BLOCK HSFE HEATER
    PARAM PRES=30.0 TEMP=70.0
BLOCK STOIC1 RSTOIC
    PARAM TEMP=70.0 PRES=150.0
    STOIC 1 MIXED C1 -1/C3 1/C5 0.5
    CONV 1 MIXED C1 1.0
BLOCK SEPSFE SEP
    PARAM PRES=14.7
    FRAC STREAM=HYD1 COMPS=C3 FRACS=1.0
    FRAC STREAM=OXYG1 COMPS=C5 FRACS=1.0
    FLASH-SPECS HYD1 PRES=14.7 TEMP=70.0
    FLASH-SPECS OXYG1 PRES=14.7 TEMP=70.0
    FLASH-SPECS REMWATER PRES=14.7 TEMP=70.0

```

```

; BLOCKS FOR SOLID WASTE INCINERATOR

```

```

BLOCK SOLIDINC RSTOIC
    PARAM TEMP=350 PRES=1067.0
    STOIC 1 CISOLID C12 -1/MIXED C5 -1/CO2 1
    CONV 1 CISOLID C12 1.0
BLOCK SOLP SEP
    PARAM PRES=14.7
    FRAC STREAM=WASC SUBSTREAM=CISOLID COMPS=C12 FRACS=1.0
    FRAC STREAM=WASC SUBSTREAM=MIXED COMPS=CO2 C5 FRACS=0.0 0.0
    FLASH-SPECS WASC PRES=14.7 TEMP=70.0 NPHASE=1 PHASE=S
    FLASH-SPECS WASCO2 PRES=14.7 TEMP=70.0 NPHASE=1 PHASE=V

```

```

BLOCK W1 CLCHNG
BLOCK W2 CLCHNG
BLOCK CHNGR8 CLCHNG
BLOCK CHNGR9 CLCHNG

```

```

; DESIGN SPECS TO SET THE CABIN ENVIRONMENT BY REGULATING THE DIFFERENT
; GAS FLOW RATES INTO THE CABIN

```

```

DESIGN-SPEC NITR
F    COMMON/USRINP/B33,B11,B44,B22,NM,NW,A88
    DEFINE A1 MASS-FLOW STREAM=INSAIR COMPONENT=C4
    SPEC A1 TO B33
    TOL-SPEC 1D-3
    VARY MASS-FLOW STREAM=N2O2 COMPONENT=C4

```

LIMITS 1D-1 50000.0

DESIGN-SPEC WAT

DEFINE A2 MASS-FLOW STREAM=INSAIR COMPONENT=C1
 SPEC A2 TO B44
 TOL-SPEC 1D-3
 VARY MASS-FLOW STREAM=CABH2O COMPONENT=C1
 LIMITS 0 1000.0

DESIGN-SPEC OXY

DEFINE A3 MASS-FLOW STREAM=INSAIR COMPONENT=C5
 SPEC A3 TO B11
 TOL-SPEC 1D-3
 VARY MASS-FLOW STREAM=N2O2 COMPONENT=C5
 LIMITS 1D-1 5000.0

DESIGN-SPEC CARDI

DEFINE A4 MASS-FLOW STREAM=INSAIR COMPONENT=CO2
 SPEC A4 TO B22
 TOL-SPEC 1D-3
 VARY MASS-FLOW STREAM=CABCO2 COMPONENT=CO2
 LIMITS 0 1000.0

CONVERGENCE ALSPC NEWTON

SPEC NITR / OXY / CARDI / WAT
 PARAM MAXIT=100

; THIS IS A FORTRAN BLOCK TO SIMULATE THE BIOLOGICAL ACTIVITIES IN A MAN
 FORTRAN MAN

```
F      COMMON/USRINP/B33,B11,B44,B22,NM,NW,A88
F      DIMENSION CA1(2),VO2(2),VCO2(2),MO2(2),VE(2),Q3(2),Q2(2)
F      DIMENSION Q1(2),YO2I3(2),YCO2I3(2),YN2I3(2),YH2OI3(2),YO2T(2)
F      DIMENSION YN2T(2),YO2M(2)
F      DIMENSION YCO2M(2),YN2M(2),YH2OM(2),YO2IM(2),YN2IM(2),YCO2T(2)
F      DIMENSION YCO2IM(2),YH2OIM(2),UR(2),H2OM(2),SWEAT(2)
F      DIMENSION TFOOD(2),TW(2),TFAT(2),TPRO(2),TCARB(2),HU(2)
F      DIMENSION CW(2),OXYG(2),HFOOD(2),DRINK(2),S(2),Q4(2)
F      REAL*8 MO2
F      DEFINE A11 MASS-FLOW STREAM=EXHAIR COMPONENT=C5
F      DEFINE A22 MASS-FLOW STREAM=EXHAIR COMPONENT=CO2
F      DEFINE A33 MASS-FLOW STREAM=EXHAIR COMPONENT=C4
F      DEFINE A44 MASS-FLOW STREAM=EXHAIR COMPONENT=C1
F      DEFINE TRACE STREAM-VAR STREAM=TC VARIABLE=MASS-FLOW
F      DEFINE WRU MASS-FLOW STREAM=FD1U SUBSTREAM=CISOLID COMPONENT=C2
F      DEFINE CAR MASS-FLOW STREAM=SOLIDW SUBSTREAM=CISOLID COMPONENT=C12
F      DEFINE OXY MASS-FLOW STREAM=WASO2 COMPONENT=C5
F      DEFINE A55 MASS-FLOW STREAM=METW COMPONENT=C1
F      DEFINE A66 MASS-FLOW STREAM=SW COMPONENT=C1
F      DEFINE A99 MASS-FLOW STREAM=FOODW COMPONENT=C1
F      DEFINE A12 BLOCK-VAR BLOCK=CAB2 SENTENCE=R-FRAC &
F          VARIABLE=FRAC ID1=AIROUT
F      OPEN(UNIT=61,FILE='INFO.DAT',STATUS='OLD')
F      OPEN(UNIT=65,FILE='SPACE.OUT',STATUS='UNKNOWN')
F      READ(61,*)NM,NW,AM,AW,WM,WW
```

```

; NM IS THE NUMBER OF MEN
; NW IS THE NUMBER OF WOMEN
; AM IS THE AVERAGE AGE OF MAN
; AW IS THE AVERAGE AGE OF WOMEN
; WM IS THE AVERAGE WT OF MAN
; WW IS THE AVERAGE WT OF WOMEN
; EEM IS THE BASAL MET ENERGY IN KCAL PER HR FOR MEN
; EEW IS THE BASAL METABOLIC ENERGY IN KCAL PER HR FOR WOMEN

F      EEM=((WM**0.5)/(0.1015*(AM**0.1333)))/24.0
F      EEW=((WW**0.5)/(0.1127*(AW**0.1333)))/24.0
F      READ(61,*)ALM,ALW
;      ALM AND ALW ARE NO OF TIMES THE BASAL ACTIVITY LEVEL IS THE ENERGY
;      EXPENDED BY THE ACTIVITY
;      LET ATM BE THE ENERGY EXPENDED BY ONE MAN IN ONE HR IN KCAL
;      LET ATW BE THE ENERGY EXPENDED BY ONE WOMAN IN ONE HR IN KCAL
F      ATM = EEM*ALM
F      ATW = EEW*ALW
;      LET RF BE THE FAT CARB RATIO
;      LET RP BE THE PROTEIN CARB RATIO
F      RF = 0.3
F      RP = 0.35
F      X = ATM
F      DO 60 I=1,2
;      CA1 IS THE AMT OF CARB REQ IN GRAMS
F      CA1(I) = X/(4.17+RF*9.3+RP*4.3)
;      VO2 IS THE AMT OF O2 REQ IN LIT
F      VO2(I) = CA1(I)*(0.85 + 0.86*RP + 2.29*RF)
;      VCO2 IS THE AMT OF CO2 REQ IN LIT
F      VCO2(I) = CA1(I)*(0.85 + 0.71*RP + 1.59*RF)
;      YO2I IS MOLE FRACTION OF O2 REQUIRED TO BE MAINTAINED IN THE CABIN
;      YN2I IS THE MOLE FRACTION OF N2 REQUIRED TO BE MAINTAINED IN THE CABIN
;      YH2OI IS THE MOLE FRACTION OF WATER VAPOR TO BE MAINTAINED IN THE
;      CABIN
;      YCO2I IS THE MOLE FRACTION OF CO2 TO BE MAINTAINED IN THE CABIN
F      YO2I = 0.208
F      YN2I = 0.769
F      YCO2I = 0.003
F      YH2OI = 0.02
;      MO2 IS THE AMT OF O2 CONSUMED IN LIT PER MIN AT STP FOR FOOD OXIDATION
F      MO2(I) = (VO2(I)/60.0)*0.88
;      WE MAKE USE OF A LINEAR RELATIONSHIP TO CALC AIR INTO THE LUNGS
;      VE IS THE VENTILLATION RATE IN LIT PER MIN AT BTP AND SATURATED
F      VE(I) = (24.55*MO2(I)) + 0.1125
;      Q3 IS THE AIR INTO THE LUNGS IN LIT PER HR
F      Q3(I) = VE(I) * 60.0
;      LET OH BE THE AMT OF WATER PRESENT IN Q1 AS ML OF WATER PER ML OF DRY
;      AIR
F      OH = (YH2OI*760.0)/(760.0 - (YH2OI*760.))
;      IN THE OUTGOING GAS AMT OF WATE PRESENT PER LIT OF DRY GAS IS
;      GIVEN BY ( 47/(760.0 -47)) = 0.066
;      LET Q2 BE THE VOL OF AIR ENTERING THE NASOPHARYNX IN LIT
F      Q2(I) = Q3(I)/((1-OH)*(1+0.066))
;      LET Q1 BE HE VOL OF AIR ENTERING THE NASAL PSG IN LIT

```

```

F      Q1(I) = Q2(I)/1.054
; NOW TO FIND OUT MOLE FRACTION OG GASES ENTERING THE LUNGS
F      YO2I3(I) = YO2I * (Q2(I)/Q3(I))
F      YCO2I3(I) = YCO2I * (Q2(I)/Q3(I))
F      YN2I3(I) = YN2I * (Q2(I)/Q3(I))
F      YH2OI3(I) = 0.062
; LET Q4 BE THE VOL OF AIR COMING OUT OF THE LUNGS IN LIT
F      S(I) = Q3(I)*(YO2I3(I)+YCO2I3(I)+YN2I3(I))
F      Q4(I) = ( S(I) - VO2(I) + VCO2(I))/0.938
; YO2T IS THE OUTPUT O2 CONC
; YCO2T IS THE OUTPUT CO2 CONC
; YN2T IS THE OUTPUT N2 CONC
F      YO2T(I) = ((Q3(I)*YO2I3(I)) - VO2(I))/Q4(I)
F      YCO2T(I) = ((Q3(I)*YCO2I3(I)) + VCO2(I))/Q4(I)
F      YN2T(I) = (Q3(I)*YN2I3(I))/Q4(I)
; TO FIND OUT AMT OF O2,N2,H2O,CO2 IN EXPIRED AIR IN LB PER HR
F      YO2M(I) = (Q4(I)*0.035*YO2T(I)*32.0)/(0.7302*558.6)
F      YCO2M(I) = (Q4(I)*0.035*YCO2T(I)*44.0)/(0.7302*558.6)
F      YN2M(I) = (Q4(I)*0.035*YN2T(I)*28.0)/(0.7302*558.6)
F      YH2OM(I) = (Q4(I)*0.035*0.062*18.0)/(0.7302*558.6)

; TO FIND OUT AMT OF GAS IN INSPIRED AIR IN LB PER HR
F      YO2IM(I) = (Q1(I)*0.035*YO2I*32.0)/(0.7302*530.0)
F      YN2IM(I) = (Q1(I)*0.035*YN2I*28.0)/(0.7302*530.0)
F      YCO2IM(I) = (Q1(I)*0.035*YCO2I*44.0)/(0.7302*530.0)
F      YH2OIM(I) = (Q1(I)*0.035*YH2OI*18.0)/(0.7302*530.0)

; LET UR BE THE AMT OF UREA IN URINE IN LB PER HR
F      UR(I) = CAL(I)*RP*0.337*0.0022
; LET H2OM BE AMT OF METABOLIC WATER PRODUCED IN LB PER HR
F      H2OM(I) = CAL(I)*(0.6 + (1.125*RF)+(0.51*RP))*0.0022
; LET SWEAT BE THE AMT OF WATER LOST AS SWEAT IN LB PER HR
F      IF(X.LE.250.0) GO TO 41
F      SWEAT(I) = ((2.5*X) - 325.0)*0.0022
F      GO TO 42
F 41      SWEAT(I) = ((1.50*X) - 75)*0.0022

; HU IS THE AMT OF WATER IN URINE IN LB PER HR
F 42      HU(I) = UR(I)*69.22
; LET TFAT BE HE TOTAL FAT IN DIET IN GM
; LET TPRO BE THE TOTAL PROTEIN IN DIET IN GM
; LET TCARB BE THE TOTAL CARB IN DIET IN GMS
F      TFAT(I) = CAL(I)*1.02*RF
F      TPRO(I) = CAL(I)*1.07*RP
F      TCARB(I) = CAL(I)*1.02
; LET TFOOD BE THE TOTAL FOOD IN DIET IN GM PER HR
F      TFOOD(I) = TFAT(I) + TPRO(I) + TCARB(I)
; LET TW BE THE TOTAL WASTE IN GM PE HR
F      TW(I) = CAL(I)*(0.02 + (0.02*RF)+(0.07*RP))
; LET CW BE THE TOTAL CARBON CONTENT OF WASTE IN GM PER HR
F      CW(I) = CAL(I)*((0.4*0.02)+(0.758*0.02*RF)+(0.312*0.07*RP))
; LET OXYG BE THE TOTAL O2 REQ TO BURN THE FECES IN LB PER HR
F      OXYG(I) = CW(I)*0.0022*(32.0/12.0)
; LET HFOOD BE AMT OF WATER IN FOOD IN LB PER HR
F      HFOOD(I) = 1.32*TFOOD(I)*0.0022

```

```

; LET DRINK BE TOTAL AMT OF POTABLE WATER REQ IN LB PER HR
F      DRINK(I)=SWEAT(I)+HU(I)+YH2OM(I)-YH2OIM(I)-HFOOD(I)-H2OM(I)
F      X=ATW
F      60      CONTINUE

; CA, P, FA ARE THE TOTAL CARBOHYDRATE, PROTEIN, FAT REQUIRED BY THE
; CREW RESPECTIVELY (GM/HR)
F      CA = TCARB(1)*NM + TCARB(2)*NW
F      FA = TFAT(1)*NM + TFAT(2)*NW
F      P  = TPRO(1)*NM + TPRO(2)*NW
F      WRITE(65,*) 'CA',CA, 'FA',FA, 'P',P

; A11,A22,A33,A44 ARE THE TOTAL AMOUNT OF O2,CO2,N2 AND WATER
; RESPECTIVELY WHICH ARE PRESENT IN THE TOTAL MASS OF EXPIRED AIR INTO ;THE
; CABIN BY ALL THE CREW MEMBERS
F      A11 = YO2M(1)*NM + YO2M(2)*NW
F      A22 = YCO2M(1)*NM + YCO2M(2)*NW
F      A33 = YN2M(1)*NM + YN2M(2)*NW
F      A44 = YH2OM(1)*NM + YH2OM(2)*NW

; B11,B22,B33,B44 ARE THE TOTAL AMOUNT OF O2,CO2,N2 AND WATER
; RESPECTIVELY WHICH ARE PRESENT IN THE TOTAL MASS OF INSPIRED AIR BY
; ALL THE CREW MEMBERS.
F      B11 = YO2IM(1)*NM + YO2IM(2)*NW
F      B22 = YCO2IM(1)*NM + YCO2IM(2)*NW
F      B33 = YN2IM(1)*NM + YN2IM(2)*NW
F      B44 = YH2OIM(1)*NM + YH2OIM(2)*NW
; LET Q6 BE THE TOTAL VOL OF INSPIRED AIR
F      Q6 = Q1(1)*NM + Q1(2)*NW
; TRACE IS THE TOTAL MASS OF TRACE CONTAMINANT STREAM WHICH IS RELATED
; TO CREW SIZE.
F      TRACE= (NM+NW)*3.27D-4
; WRU IS THE TOTAL UREA PRODUCED BY THE CREW
F      WRU = UR(1)*NM + UR(2)*NW
; LE TOTW BE THE TOTAL AMOUNT OF SOLID WASTE GENERATED BY THE CREW
F      TOTW = TW(1)*NM + TW(2)*NW
; CAR IS THE CARBON PRESENT IN THE TOTAL SOLID WASTE FROM THE CREW
F      CAR = (CW(1)*NM + CW(2)*NW)*0.0022
F      WRITE(65,*) 'TOTW',TOTW, 'CAR',CAR
; LEP PER BE TOTAL % OF CARBON IN WASTE
F      PER = CAR/(TOTW)*0.0022
F      WRITE (65,*) 'PER',PER
; OXY IS THE TOTAL O2 REQUIRED FOR SOLID WASTE INCINERATOR
F      OXY = OXYG(1)*NM + OXYG(2)*NW
; A55 IS TOTAL METABOLIC WATER PRODUCED BY ALL THE CREW MEMBERS
F      A55 = H2OM(1)*NM + H2OM(2)*NW
; A66 IS THE TOTAL SWEAT GENERATED BY ALL THE CREW MEMBERS
F      A66 = SWEAT(1)*NM + SWEAT(2)*NW
; A77 IS THE TOTAL AMOUNT OF WATER ASSOCIATED WITH THE UREA AS URINE
F      A77 = HU(1)*NM + HU(2)*NW
; A88 IS THE TOTAL POTABLE WATER TO BE SUPPLIED AS DRINKING WATER
F      A88 = DRINK(1)*NM + DRINK(2)*NW
; A99 IS THE TOTAL WATER ASSOCIATED IN THE FOOD REQUIRED BY THE ENTIRE
; CREW
F      A99 = HFOOD(1)*NM + HFOOD(2)*NW

```

```

; LET THEAT BE THE TOTAL HEAT LIBERATED BY THE CREW IN BTU
F   THEAT = (NM*ATM + NW*ATW)*(4187.0/1055.0)
; LET THE BUFFER TEMP OF THE GASES SUPPLIED TO THE CABIN BE 69 F
; LET Q5 BE THE VOL OF AIR TO BE SUPPLIED
F   Q5 = THEAT/(1.08*1.0)
F   A10 = (Q5*60.0)/(Q6*0.035)
F   A12 = A10 / (1+A10)
F   WRITE(65,*) 'A99',A99, 'A88',A88, 'A12',A12

WRITE-VARS A11 A22 A44 A33 TRACE WRU CAR OXY A55 A99 A66 &
      A12
FLASH-SPECS EXHAIR TP NPHASE=1
FLASH-SPECS METW NOFLASH
FLASH-SPECS FOODW NOFLASH

; THIS IS A FORTRAN BLOCK TO REGULATE THE WATER REQUIRED FOR SATURATING
; THE EXPIRED AIR
FORTRAN WSEPMAN
  DEFINE WSEP1 MASS-FLOW STREAM=INSAIR COMPONENT=C1
  DEFINE WSEP2 MASS-FLOW STREAM=EXHAIR COMPONENT=C1
  DEFINE WSEP3 BLOCK-VAR BLOCK=WASEP SENTENCE=MASS-FLOW &
    VARIABLE=FLOW ID1=WAEXH
  DEFINE WSEP4 MASS-FLOW STREAM=SW COMPONENT=C1
  DEFINE WSEP5 BLOCK-VAR BLOCK=WASEP SENTENCE=MASS-FLOW &
    VARIABLE=FLOW ID1=SW1
F   WSEP3 = WSEP2 - WSEP1
F   WSEP5 = WSEP4
  EXECUTE BEFORE WASEP

; THIS DESIGN SPEC IS USED TO REGULATE THE AMOUNT OF CO2 REMOVED BY
; ENSURING THAT AMOUNT OF CO2 IN THE AIR STREAM IS WHAT IS DESIRED TO BE
; SUPPLIED TO THE CABIN. HERE WE MAKE AN ASSUMPTION THAT THE EQUIPMENT
; IS AVAILABLE TO ACHIEVE THE DESIRED SEPARATION.
DESIGN-SPEC SEPATR
  DEFINE SEP1 MASS-FLOW STREAM=ABAIR1 COMPONENT=CO2
  DEFINE SEP2 MASS-FLOW STREAM=CABCO2 COMPONENT=CO2
  SPEC SEP1 TO SEP2
  TOL-SPEC 1D-3
  VARY BLOCK-VAR BLOCK=SEP3 SENTENCE=FRAC &
    VARIABLE=FRACS ID1=MIXED ID2=ABAIR1 ELEMENT=1
  LIMITS 0 1.0

; THIS FORTRAN BLOCK IS USED TO ADJUST THE AMOUNT OF H2 TO BE SUPPLIED
; TO THE BOSCH PROCESS.
FORTRAN H2ADJUST
  DEFINE HY1 MASS-FLOW STREAM=HYDRO COMPONENT=C3
  DEFINE HY2 MASS-FLOW STREAM=SEPOUT2 COMPONENT=C3
  DEFINE HY3 STREAM-VAR STREAM=HYDRO VARIABLE=VFRAC
  DEFINE CO1 STREAM-VAR STREAM=SEPC VARIABLE=MASS-FLOW
  DEFINE CO4 STREAM-VAR STREAM=WASCO21 VARIABLE=MASS-FLOW
  DEFINE CO5 MASS-FLOW STREAM=SEPOUT2 COMPONENT=CO2
F   HY1 = 2*(CO1+CO5+CO4) - HY2
F   HY3 = 1.0
F   WRITE(65,*) 'HY1',HY1, 'HY3',HY3
  READ-VARS HY2 CO1 CO5 CO4

```

WRITE-VARS HY1 HY3

; THIS FORTRAN BLOCK IS USED TO CONTROL THE TEMPERATURE OF THE
; DEHUMIDIFIER FOR THE EXIT AIR FROM THE CABIN.

FORTRAN HUMIDIFICATION

```

      DEFINE HU1 MASS-FLOW STREAM=HUHXOUT COMPONENT=C1
      DEFINE HU2 MASS-FLOW STREAM=CABH2O COMPONENT=C1
      DEFINE HU2A BLOCK-VAR BLOCK=HEA2 SENTENCE=FRAC &
        VARIABLE=FRACS ID1=MIXED ID2=CAIR ELEMENT=1
      DEFINE HU3 STREAM-VAR STREAM=HUHXOUT VARIABLE=MASS-FLOW
      DEFINE HTEMP STREAM-VAR STREAM=HUHXOUT VARIABLE=TEMP
      DEFINE HTSEP1 BLOCK-VAR BLOCK=HEA2 SENTENCE=FLASH-SPECS &
        VARIABLE=TEMP ID1=WA
      DEFINE HTSEP2 BLOCK-VAR BLOCK=HEA2 SENTENCE=FLASH-SPECS &
        VARIABLE=TEMP ID1=CAIR
F      HU4 = HU3 - HU1
F      HU2A = HU2/HU1
F      HYIN = HU1/HU4
F      HYOUT = HU2/HU4
F      LABAS = 1075.8
F      CS = 0.24 + 0.45*HYIN
F      HU5 = ((HYIN - HYOUT)*LABAS)/CS
F      HTSEP1 = HTEMP - HU5
F      HTSEP2 = HTEMP - HU5
F      WRITE(65,*) 'HTSEP2', HTSEP2, 'HU5', HU5
      READ-VARS HU1 HU2 HU3 HTEMP
      WRITE-VARS HTSEP1 HTSEP2 HU2A

```

; THIS DESIGN SPEC IS USED TO REGULATE THE AMOUNT OF WATER TO BE
; SUPPLIED FOR DRINKING. THIS ENABLES TO COMPLETELY CLOSE THE WATER
; LOOP. THE REMAINING WATER IS SENT TO THE WATER ELECTROLYSIS UNIT.

DESIGN-SPEC MAKEUPPOT

```

      DEFINE AK1 MASS-FLOW STREAM=MAKEUPPOT COMPONENT=C1
      DEFINE AK2 MASS-FLOW STREAM=DECAN COMPONENT=C1
      DEFINE AK3 MASS-FLOW STREAM=WA1 COMPONENT=C1
F      AK5 = A88 - (AK2+AK3)
F      IF(AK5.LE.0.0) GO TO 71
F      AK6 = AK5
F      GO TO 72
F 71      AK6 = 0.0
F 72      WRITE(65,*) 'AK6', AK6
      SPEC AK1 TO AK6
      TOL-SPEC 1D-3
      VARY BLOCK-VAR BLOCK=SPTT4 SENTENCE=FRAC &
        VARIABLE=FRAC ID1=MAKEUPPOT
      LIMITS 0 1.0

```

; THIS FORTRAN BLOCK IS USED TO COMPUTE THE AMOUNT OF MAKEUP HYGIENE
; WATER REQUIRED

FORTRAN HYGIENEMAKUP

```

      DEFINE U11 MASS-FLOW STREAM=S2 COMPONENT=C1
      DEFINE U12 MASS-FLOW STREAM=MAKEUPS2 COMPONENT=C1
F      OPEN(UNIT=90, FILE='WA.OUT', STATUS='UNKNOWN')
;      LET U13 BE THE FLOW RATE OF MAKE UP HYGIENE WATER

```

```

F      U13=2.29*(NM+NW)-U11
F      IF(U13.LT.0.0) GO TO 311
F      U12=U13
F      GO TO 312
F 311   U12=0.0
F 312   WRITE(65,*) U12,'AMT OF MAKUP HYGIENE WATER'
        EXECUTE BEFORE MIX18
        FLASH-SPECS S2 NOFLASH
        FLASH-SPECS MAKEUPS2 NOFLASH

; THIS IS A FORTRAN BLOCK TO MAINTAIN THE UREA CONC AS DESIRED IN THE
; THE HYGIENE WATER
FORTRAN URMaint
  DEFINE R1 MASS-FLOW STREAM=S21 SUBSTREAM=CISOLID COMPONENT=C2
  DEFINE R2 STREAM-VAR STREAM=SS2 SUBSTREAM=CISOLID VARIABLE=MASS-FLOW
F      OPEN(UNIT=90,FILE='WA.OUT',STATUS='UNKNOWN')
F      R22 = 5.5D-5*(NM+NW) - R1
F      IF(R22.LT.0.0) GO TO 410
F      R2=R22
F      GO TO 411
F 410   R2=0.0
F 411   WRITE(65,*)R2,'MASS FLOW OF SS2'
        EXECUTE BEFORE MIX15
        FLASH-SPECS S21 NOFLASH
        FLASH-SPECS SS2 NOFLASH

; THIS IS A FORTRAN BLOCK TO COMPUTE THE MAKEUP URINAL FLUSH WATER
; REQUIRED
FORTRAN FLUSHMAK
  DEFINE FL1 MASS-FLOW STREAM=S1 COMPONENT=C1
  DEFINE FL2 MASS-FLOW STREAM=URFLUSH COMPONENT=C1
F      FL3=(0.0454*(NM+NW)) - FL1
F      IF(FL3.LT.0.0)GO TO 99
F      FL2=FL3
F      GO TO 97
F 99    FL2=0.0
F 97    WRITE(65,*)'URFUSH REQ',FL2
        EXECUTE BEFORE MIX20
        FLASH-SPECS S1 NOFLASH

; THIS FORTRAN BLOCK IS USED TO DETERMINE THE SPLIT FRACTION FOR THE
; PURE OBTAINED FROM THE WATER REGENERATION UNIT AS IN SPTT3
FORTRAN WATERSPLIT
  DEFINE WA1 STREAM-VAR STREAM=CON3 VARIABLE=MASS-FLOW
  DEFINE WA2 BLOCK-VAR BLOCK=SPTT3 SENTENCE=MASS-FLOW &
        VARIABLE=FLOW ID1=S1
  DEFINE WA3 BLOCK-VAR BLOCK=SPTT3 SENTENCE=MASS-FLOW &
        VARIABLE=FLOW ID1=S2
; LET HY BE THE AMOUNT OF WATER REQ FOR HYGIENE PURPOSE
; LET FLU BE THE AMOUNT OF WATER REQ FOR FLUSH PURPOSE
; THESE ABOVE VALUES ARE OBTAINED FROM NASA DATA BASE FOR A CREW OF ONE
; MEMBER
F      HY=2.29 * (NM+NW)
F      FLU=0.0454*(NM+NW)
;LET WA5 BE THE DIFF BETWEEN CON3 AND FLU AND HY

```

```

F      WA5=WA1 - (HY + FLU)
F      IF(WA5.LT.0.0)GO TO 13
F      WA2 = FLU
F      WA3 = HY
F      GO TO 133
F 13   WA2=0.02*WA1
F      WA3=0.98*WA1
F 133  WRITE(65,*) 'WA2',WA2,'WA3',WA3
      EXECUTE BEFORE SPTT3
      FLASH-SPECS CON3 NOFLASH

```

; THIS FORTRAN BLOCK IS USED TO COMPUTE THE SPLIT FRACTION FOR THE
; CATALYTIC OXIDATION IN THE TRACE GAS TREATMENT SUBSYSTEM
FORTRAN TRACRAT

```

      DEFINE TR1 MASS-FLOW STREAM=OUTM COMPONENT=C6
      DEFINE TR2 STREAM-VAR STREAM=OUTM VARIABLE=MASS-FLOW
      DEFINE TR3 BLOCK-VAR BLOCK=SPLT1 SENTENCE=FRAC &
        VARIABLE=FRAC ID1=HT
F      TR4 = TR1/TR2
F      TR5 = (0.075/0.08)*TR4
F      IF (TR5.LE.0.075)GO TO 92
F      TR7 = TR5
F      GO TO 93
F 92   TR7 = 0.075
F 93   IF (TR7.GT.0.3)GO TO 95
F      TR3=TR7
F      GO TO 96
F 95   TR3 = 0.3
F 96   WRITE(65,*) 'TR3',TR3
      EXECUTE BEFORE SPLT1

```

; THIS FORTRAN BLOCK IS USED TO COMPUTE THE AMOUNT OF EXPENDABLES
; STORED/CONSUMED FOR THE ENTIRE LSS
FORTRAN REQUIREMENTS

```

      DEFINE RHQ2 MASS-FLOW STREAM=HYD1 COMPONENT=C3
      DEFINE RHQ3 MASS-FLOW STREAM=HYDRO COMPONENT=C3
      DEFINE RCQ4 MASS-FLOW STREAM=ABAIR COMPONENT=CO2
      DEFINE RCQ5 MASS-FLOW STREAM=CABCO2 COMPONENT=CO2
      DEFINE RNQ6 MASS-FLOW STREAM=ABAIR COMPONENT=C4
      DEFINE RNQ7 MASS-FLOW STREAM=N2O2 COMPONENT=C4
      DEFINE ROQ8 MASS-FLOW STREAM=N2O2 COMPONENT=C5
      DEFINE ROQ9 MASS-FLOW STREAM=ABAIR COMPONENT=C5
      DEFINE ROQ10 MASS-FLOW STREAM=OXYG1 COMPONENT=C5
      DEFINE RWQ12 MASS-FLOW STREAM=CABH2O COMPONENT=C1
      DEFINE ROQ13 MASS-FLOW STREAM=WASO2 COMPONENT=C5
      DEFINE RWQ14 MASS-FLOW STREAM=MAKEUPS2 COMPONENT=C1
      DEFINE RWQ15 MASS-FLOW STREAM=URFLUSH COMPONENT=C1
      DEFINE RWQ16 MASS-FLOW STREAM=ABAIR COMPONENT=C1
      DEFINE RWQ17 STREAM-VAR STREAM=SOLIDC SUBSTREAM=MIXED &
        VARIABLE=MASS-FLOW
F      OPEN(UNIT=66,FILE='REPORT.OUT',STATUS='UNKNOWN')
; H2REQ IS AMT OF H2 IN BUFFER
F      H2REQ = RHQ2 - RHQ3
F      CO2REQ = RCQ5 - RCQ4
F      N2REQ = RNQ7 - RNQ6

```

```

; O2REQ IS AMT OF O2 STORED IN BUFFER
F      O2TCAB = ROQ8 - ROQ9
F      O2REQ =ROQ10 + ROQ9 -ROQ13 - ROQ8
F      WATREQ = RWQ12+RWQ14+RWQ15-RWQ16
F      WRITE(66,*)'NM:',NM,'NW:',NW
F      WRITE(66,*)'AMOUNT OF WATER REQ:',WATREQ
F      WRITE(66,*)'AMOUNT OF OXY REQ:',O2REQ
F      WRITE(66,*)'AMOUNT OF CO2 REQ:',CO2REQ,'AMT OF N2 REQ:',N2REQ
F      WRITE(66,*)'AMOUNT OF H2 REQ:',H2REQ
F      WRITE(66,*)'CARBO:',CA,'FAT:',FA,'PROTEIN:',P
F      WRITE(65,*)'AMOUNT OF SOLIDC',RWQ17
      READ-VARS RHQ2 RHQ3 RCQ4 RCQ5 RNQ6 RNQ7 ROQ8 ROQ9 ROQ10 &
          RWQ12 ROQ13 RWQ14 RWQ15 RWQ17

; THIS IS A FORTRAN BLOCK TO DETERMINE THE WASTE OXIDIZER TEMP( A LINEAR
; RELATIONSHIP IS USED)
FORTRAN WASOTEMP
      DEFINE CTEMP BLOCK-VAR BLOCK=SOLIDINC SENTENCE=PARAM &
          VARIABLE=TEMP
      CTEMP = (((194 - PER)/0.65)*(9/5)) + 32
F      WRITE(65,*)'CTEMP',CTEMP,'PER',PER
      WRITE-VARS CTEMP

; THIS IS A FORTRAN BLOCK TO DETERMINE THE AMOUNT OF WATER IN BRINE.
; THIS IS TO ENSURE THAT THE OUTPUT FROM THE VCD IS A 45% CONCENTRATED
; SOLUTION
FORTRAN VCD
      DEFINE VCD1 MASS-FLOW STREAM=FOUT SUBSTREAM=CISOLID COMPONENT=C2
      DEFINE VCD2 MASS-FLOW STREAM=FOUT COMPONENT=C1
      DEFINE VCD3 BLOCK-VAR BLOCK=STILL SENTENCE=FRAC &
          VARIABLE=FRACS ID1=MIXED ID2=BRINE ELEMENT=1
F      VCD4 = 0.45*VCD1
F      VCD3 = VCD4/VCD2
F      WRITE(65,*)'VCD3',VCD3
      READ-VARS VCD1 VCD2
      WRITE-VARS VCD3

; THIS IS A FORTRAN BLOCK TO DOUBLY ENSURE THAT THE RIGHT AMOUNT OF
; POTABLE WATER IS SUPPLIED TO THE CABIN. THE EXCESS IS SENT FOR O2
; GENERATION
FORTRAN POTAD
      DEFINE POT1 BLOCK-VAR BLOCK=POTSEP SENTENCE=MASS-FLOW &
          VARIABLE=FLOW ID1=PW01
F      POT1 = A88
F      WRITE(65,*)'POT1',POT1
      EXECUTE AFTER POTMIX

CONV-OPTIONS
      PARAM TEAR-METHOD=WEGSTEIN TOL=0.0001
      WEGSTEIN MAXIT=200

RUN-CONTROL MAX-TIME=4000

BLOCK-REPORT NEWPAGE

```